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The Use and Efficiency of Some Gutter Inlet Grates

by

John C. Guillou

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ABSTRACT

The development of an adequate and economical highway drainage system depends to a large degree upon the judicious use of gutters and gutter inlet grates. Gutters are usually provided adjacent to highway pavements to control excessive ponding of precipitation runoff, or to prevent erosion or saturation of the roadway shoulder. Another function of the highway gutter is to concentrate runoff so it may be intercepted and disposed of economically through the use of a sub-surface sewer system.

The function of the gutter inlet grate is to intercept water flowing in the gutter, and to reject trash and large debris which might cause stoppage in the subsurface flow system.

During the past few years considerable progress has been made toward the development of a truly efficient gutter inlet grate. This progress is the result of greater interest and attention on the part of the highway design engineer and an increased volume of theoretical and experimental studies on the subject. The purpose of this report is to present design relationships applicable to a series of typical inlet grates developed in a previous laboratory study. The program was conducted cooperatively with the Illinois Division of Highways, and the University of Illinois Engineering Experiment Station.

The research program consisted primarily of an experimental determination of the interception characteristics of four Illinois Division of Highways standard inlet grates and frames. In addition to the experiment, a theoretical analysis of some of the factors which enter into the efficiency and use of gutter inlet grates was completed.

The laboratory investigation required the construction of a full scale model 42 ft long. The model structure included four removable channel sections built to the exact cross-sectional dimensions of the four standard inlet grate frames used in the test program. The longitudinal slope of the model was variable so that the effect of various gutter slopes could be studied. The laboratory test program consisted of the determination of interception efficiency curves for the previous and present standard inlet grate design.

The theoretical portion of the research program included the development of rating curves for three standard pavement sections. The experimental inlet grate efficiency data were re-arranged so they could be applied to any of the three pavement sections. The theoretical analysis also developed two examples to show how experimental data could be applied to a typical design problem.

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FIGURES (Concluded)

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I. INTRODUCTION

The investigation described in this report resulted from an earlier program conducted at the University of Illinois. During 1947, the Illinois Division of Highways, in cooperation with the U. S. Bureau of Public Roads, sponsored a research program to aid development of more efficient drainage structures for the West Route Express Highway in Chicago, Illinois. The results of this program could also be applied to similar problems elsewhere.

One phase of that program required constructing and testing a one-to-three scale model of a portion of the Express Highway pavement with adjacent gutters and gutter inlets. A major result produced by this investigation was the substitution of parallel bar inlet grates for the previously accepted parallel and transverse bar grates.

After evaluating the results of the experimental investigation, in 1953 the Illinois Division of Highways revised all of the inlet grate standards so they would more nearly conform with the findings of the scale model study. Laboratory space and apparatus were not available at that time, so it was not possible to determine the actual rating curves for the newly adopted state standards.

This research schedule was undertaken during 1954 to provide the required interception efficiency data for the four most widely used standard inlet grates which had been adopted in 1953.

1. Object of Investigation

The objective of this program was to present a report giving information pertinent to the solution of typical gutter design problems. Such problems include not only the flow and interception of water in the roadway gutters, but also the flow of water on the adjacent portions of the roadway pavement. Satisfaction of the objective, therefore, required the preparation of flow capacity curves for combined pavement and gutter flow sections.

The primary purpose of the experimental portion of the research program was the production of interception efficiency curves for some of the Illinois Division of Highways standard inlet grates. This information was transposed to provide interception efficiency data for the combined prototype gutter and pavement flow sections.

The secondary objective of the experimental program was the calibration of the corresponding old-style standard inlet grates. This was included in the study so a comparison could be made of the interception efficiencies of the two styles of inlet grate.

2. Scope of Investigation

This report is limited to information relative to four specific standard inlet grate designs selected as most representative of the Division of Highways installations. It is estimated that over 80% of the gutter inlets installed by the Division of Highways are represented by the four types considered here.

Table 1 lists the types of grates tested in the laboratory and a brief description of the gutter types.

Table 1

Gutter-Inlet Grate Test Combinations

Frame and Grate Type*	Gutter	Description	Remarks
3	Type 6	24-in. wide gutter with barrier curb	Tested with and without curb opening interception
9	Type A	36-in. wide "V" gutter	
10	Type B	21-in. wide "V" gutter	
11	Type 3	12-in. wide gutter with barrier curb	Tested with and without curb opening interception

* Illinois Division of Highways classification number.

Curves showing the relationship between the total rate of flow approaching the inlet grate and the rate of flow intercepted by the inlet grate were prepared for each of the test combinations. This work was completed with longitudinal gutter slopes equal to 0.125, 0.250, 0.500, 1.00, 2.00, 4.00, and 6.00%.

Inlet grate rating curves, similar to those described in the preceding paragraph, were also prepared for the corresponding old-style inlet grates.

II. INLET GRATE USE AND EFFICIENCY

In spite of the large amount of attention accorded the interception characteristics of inlet grates, relatively little has been said about their functional use. All too often inlet grates are installed at locations where the gutter flow might be intercepted with other types of structures, or where the screening of the intercepted flow is neither necessary nor desirable. The following discussion is presented with the belief that many inlet grate installations could be eliminated, substantially reducing drainage costs.

The discussion is based on the fact that the inlet grate is primarily a hydraulic or drainage installation. This requires that the structural aspects of the installation be designed in accordance with the hydraulic characteristics, and not vice versa.

3. Function of Inlet Grates

The chief hydraulic function of an inlet grate is to remove trash and debris from storm water flow. In order to prevent stoppage in subsurface conduits, storm water must be free of objectionable foreign material. Floating trash, such as branches and twigs from trees or bushes, large leaves, newspapers, tin cans, and similar highway litter, may easily lodge in the drain pipe and form serious flow obstructions. Therefore, efficient inlet grates must be designed to prevent the entry of large floating or entrained trash and litter.

The grating must also exclude from the sewer large detritus, such as gravel and stones, which might settle in the sewer and thus reduce the capacity of the subsurface system. Small detritus, with major dimension less than about 1 in., is not ordinarily excluded by the screening action of the inlet grating. This type of material may be best removed from the intercepted flow with a sedimentation type of desilting structure. The operating characteristics of the desilting structure are best determined in accordance with the sediment transport capacity of the downstream sewer system.[2]

The secondary hydraulic function of an inlet grating is the interception of storm water. The interception capacity of any grating in a given gutter section is determined by two distinct characteristics. The first is the geometrical characteristics of the grating. The grating that presents the best flow-through area will intercept the greatest amount of storm water. The other characteristic is the self-cleaning capacity of the inlet grate. This factor is of great importance since the accumulation of trash on the inlet grate causes a direct decrease in the amount of flow-through area presented to the storm water.

The third function of an inlet grate is of a structural nature. The grate must have sufficient strength to support the physical loads imposed upon it by traffic. The design loading must consider not only the wheel loads from normal traffic, but must also allow for impact loads. These impact loads may be caused by wheel loads dropping from curb height at corner installations, or by wheels striking the upper portion of the grate in cases where the grating extends upward into the plane of the curb face.

The final functional requirements of any grating design are the practical and economic characteristics. Included in this category are the cost of grating and frame, the useful life of the grating and frame, the advantages of standardized designs, and maintenance features such as ease of removal and replacement.

All these functions must be satisfied with a single design. However, the guiding design principle is that the grating must remove trash and large detritus and still maintain high interception efficiency. It is just as illogical to install hydraulically efficient gratings with inadequate strength as it is to install a structurally sound design with unsatisfactory hydraulic characteristics. An acceptable design results from an evaluation of all factors along with the compatible satisfaction of each.

4. Use of Inlet Grates

In highway drainage work, gutter inlet grates ordinarily are used only in conjunction with paved roadside gutters. Gutters are installed in rural areas to prevent erosion of the roadway shoulder adjacent to the pavement or to avoid saturation of the shoulder by runoff from the pavement area. Further use of gutters is sometimes made where the highway is passing through a cut section if it is necessary to pave the ditch between the cut slope and the roadway shoulder to prevent erosion.

In many cases, rural gutters do not need to be equipped with inlet grates. The use of a gutter turn-out or a simple curb opening type inlet will often be adequate. The curb opening inlet may discharge into a subsurface conduit or into a simple paved ditch, but in either case the inlet grate and frame usually can be eliminated. Since the turn-out type of structure is generally more economical to construct, it should be used whenever possible.

The majority of inlet grates are used in urban or suburban areas. In this type of installation the physical spacing of the inlets is often dictated by the length of block, as it is not desirable to carry gutter flow through intersections. If this criterion is followed in locating gutter inlets, the flow rate will be relatively low since the drainage area is restricted to one or two blocks. In the case of limited access roadways or areas with long, deep blocks, the drainage area served by a single inlet grate may be large. With the resulting high flow rates, the inlet grate must be able to function efficiently.

The inlet grating is used to separate trash and large detritus from the storm water flow and to pass the intercepted flow to the subsurface drainage system. As a result of the separation action, debris will normally accumulate on the grating or in the gutter just downstream from the inlet. This imposes a location restriction on the designer.

The inlet grate should be installed off the traveled area to avoid the packing of debris by traffic. While an efficient parallel bar inlet grate will exhibit good self-cleaning characteristics, it is not reasonable to expect the gutter flow to move debris that has become matted and packed into the grate openings. For this reason inlets should not be installed at the corners of intersections. At intersections, the most satisfactory inlet location is in the straight section of gutter just upstream from the pedestrian crossing. Such a location has the dual advantages of being out of the normal path of vehicles and also of removing the gutter flow upstream from the sidewalk crossing. Thus, debris packing is reduced and pedestrians can cross the gutter where the flow rate is lowest and the water width the least.

III. FACTORS INFLUENCING INTERCEPTION EFFICIENCY

5. Definition

The interception efficiency of an individual inlet grate, normally expressed as a percentage, is defined as the ratio of the intercepted flow to the total flow in the gutter and adjacent portions of the roadway.

The efficiency of an inlet grate system depends on many factors. Some pertain to the inlet grate itself, and others pertain to the entire drainage system. Factors in the major drainage system that influence interception efficiency are inlet spacing interval, characteristics of the approach gutter, volume of flow in the gutter compared to the volume on the pavement, and ability of the sub-surface system to dispose of the intercepted flow. The inlet grate factors that influence interception efficiency are the geometrical pattern, the flow-through area, and the ability to handle detritus and floating trash. Figure 1 shows some of the characteristics of a typical inlet in a gutter drainage system.

6. The Spacing Interval

Considering any given width of drainage area and precipitation intensity, the spacing interval upstream from the inlet is the predominant factor governing the total rate of storm water flow that is presented to the inlet. This may be demonstrated by using the rational formula for computing the rate of runoff. The equation is:

$$Q = CIA \tag{1}$$

where Q is the runoff rate in cu ft per sec, I is the rainfall intensity, in. per hr, A is equal to the drainage area in acres, and C is a coefficient dependent on the relative imperviousness of the drainage area. It should be noted that the expression is not dimensionally homogeneous. The rainfall intensity, I, is determined by considering both the design frequency and the time of equilibrium. The time of equilibrium is defined as the time required for water from the most chronologically remote point to reach the point of concentration.

Equation 1 may be expressed in terms of the drainage area dimensions as follows:

$$Q = 0.230CILW \times 10^{-4} \tag{2}$$

where L and W are the length and width of the rectangular drainage area, both dimensions expressed in ft.

Examination of Eq. 2 shows that for a given rainfall intensity and drainage area width, C and L are the only factors affecting the dependent variable, Q. The width of the drainage area is usually fixed by the geometry of the roadway system. The factor C, which is the imperviousness coefficient, is dependent upon the mean imperviousness of the entire drainage area. Extending the length of the drainage area, which is equivalent to increasing the inlet spacing interval, usually will not significantly affect the imperviousness coefficient. This is because C represents a composite surface, making it relatively independent of the length of the drainage area. Therefore, the length of the drainage area, L, is the predominant factor governing the generation of precipitation runoff.

If the drainage design is based on a fixed precipitation frequency, any increase in the length of the drainage area will cause a corresponding decrease in the rainfall intensity, I, since it will increase the time of concentration. For any frequency, the rainfall intensity is an inverse function of the time of concentration. Reduction in the rainfall intensity will tend to decrease the total runoff rate, Q, when calculated by Eq. 2. However, only in extremely unusual circumstances will this counteract the increase in runoff caused by lengthening the drainage area. The factor L changes much more rapidly than does the rainfall intensity factor.

Figure 1 shows the drainage area associated with the inlet interval, L. The upper and lower limits of the drainage area originate at the downstream end of the inlet grates and extend toward the roadway centerline. For the usual design case, the limit lines may be assumed to be straight and perpendicular to the curb line.

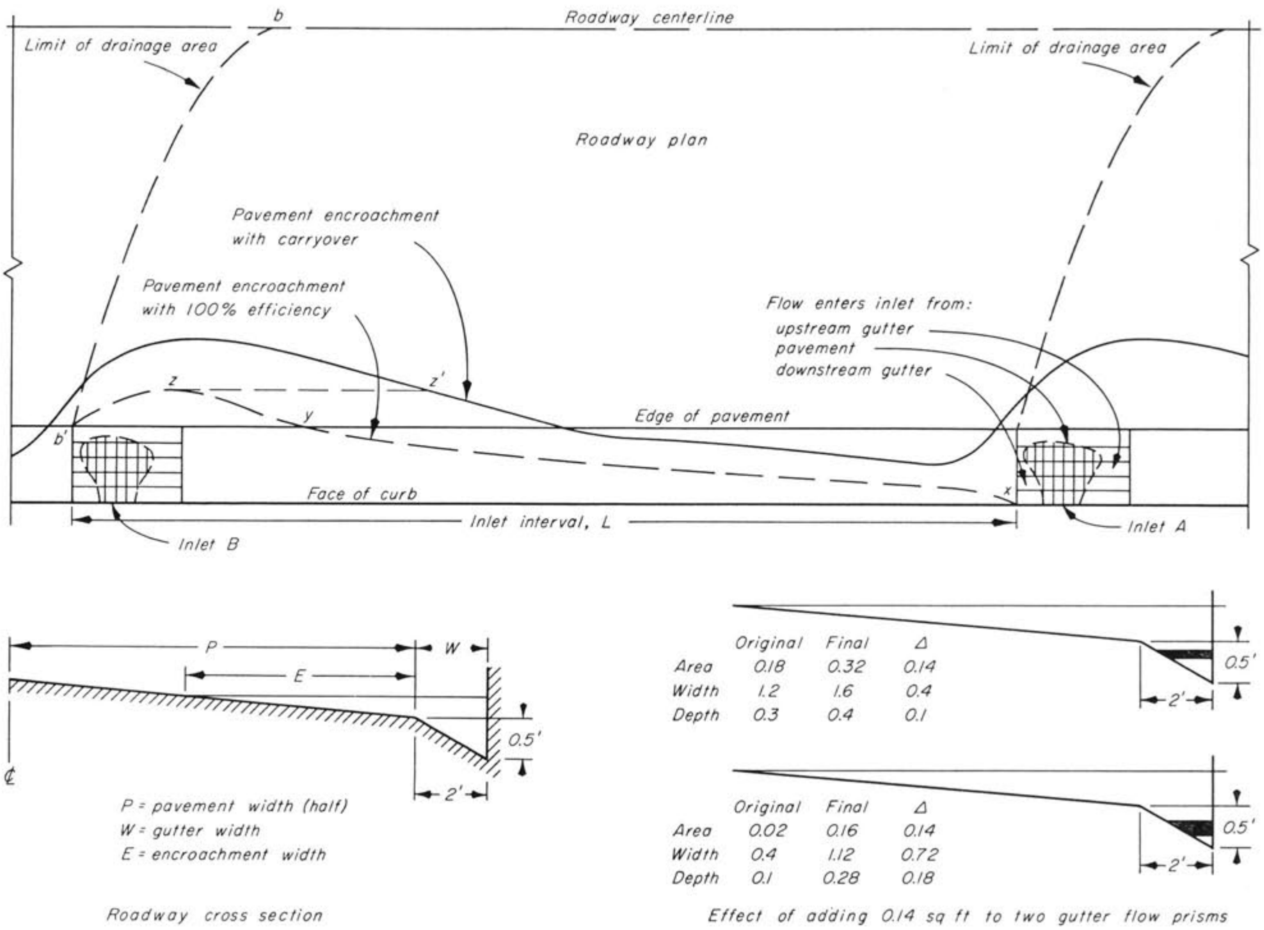


Fig. 1. Diagram of Gutter and Pavement Flow Patterns

In certain cases this assumption will lead to a poorly balanced design and possibly to an inoperable system. Therefore, the mechanics of flow on the drainage area should be thoroughly understood. For the purposes of this discussion, it is assumed that all of the flow in the gutter at Inlet B, Fig. 1, originated on the drainage area bounded by the two dashed limit lines, the curb face, and the roadway centerline. The width of gutter flow is shown by the dashed line $xyzb'$. It is assumed that the pavement crown is positive and symmetrical about the roadway centerline.

The curb face and the roadway centerline are physical limits of the drainage area and are unaffected by the longitudinal slope of the roadway. The transverse limits of the pavement drainage area are not physical, but kinematic. Therefore, the longitudinal slope and the cross slope, or crown, are of primary importance in determining the exact length of the drainage area.

If the line denoting the lower limit of the drainage area on Fig. 1 is considered in detail, certain facts become apparent. The boundary line, bb', is the path followed by pavement runoff at the lowest and most remote point on the drainage area. Pavement runoff, originating from a point below line bb', will not be presented to Inlet B. Runoff originating at a point within the drainage area will be presented to Inlet B, either directly or after flowing in the gutter.

If both the crown of the roadway and the longitudinal slope are constant throughout the length L, every pavement flow path will be parallel to the lower boundary. Therefore the upper and lower limits of the drainage area must be parallel to each other.

The shape of the runoff path, line bb', is a function of the kinematic properties of the pavement crown and longitudinal slope. At any point, the tangent to the flow path is determined by the vector sum of the longitudinal slope and the pavement cross slope. When the cross slope is uniform, the path of flow will be a straight line, and when the cross slope, or crown, is curved, the path of flow will be curved. Since the runoff path is proportional to the vector sum of the longitudinal and transverse slopes, when the cross slope is constant and equal to the longitudinal slope, the flow line will be straight and at an angle of 45° to the roadway centerline. Similarly, when the cross slope is greater than the longitudinal slope, the flow path will be at an angle of between 45° and 90° to the downstream portion of the roadway centerline. The flow line will be at an angle of less than 45° to the centerline when the cross slope is less than the longitudinal slope.

These facts may also be applied to a pavement with curvilinear crown. The only difference is that the flow path is a curve, and the curve is composed of a series of vectors, each proportional to the vector sum of the longitudinal and cross slope at the given point. The upper and lower limits of the area in Fig. 1 represent a pavement with curvilinear crown. It may be noted that the boundary line will always be either concave upward or straight. A concave downward flow path would require decreasing the cross slope from the centerline which is a rare condition.

When the slope of the roadway pavement is mild, the exact path of flow is not significant. However, when the longitudinal slope is steep, the flow path becomes very important. Figure 2 illustrates the difficulties which may be encountered when the inlet interval is not selected according to the longitudinal slope of the pavement. The two roadway sections are of equal length and width with equal interval between the units of the inlet series. For simplicity, it is assumed the roadway cross slope is uniform and, therefore, the flow paths are straight lines.

Reference to the portion of the figure pertaining to a mild pavement slope indicates that the individual drainage areas can, for all practical purposes, be assumed to be rectangular. It can be seen from the flow paths that this assumption will cause Inlet No. 1 to receive slightly less than the design runoff. Inlet No. 4, located at the bottom of the roadway sag, will receive slightly more than the design flow.

If the roadway slope is steep, the inlet drainage areas may not be considered rectangular as illustrated by the steep slope portion of Fig. 2. The example assumes a cross slope of 1% and a longitudinal slope of 10%. Under this condition Inlet No. 1 receives only 66% of the flow originating on the rectangular drainage area and thus the inlet will operate at less than design capacity. Although this is not economical, it is not harmful. The failure of the system designed on the rectangular drainage area assumption occurs at Inlet No. 4, located at the bottom of the sag. Inlet No. 4 is required to intercept all of the flow that originated on the rectangular area, plus the portion of the flow that bypassed Inlet No. 1. In this example, the flow presented to Inlet No. 4 will be 133% of the design flow. If the system was designed for reasonably high gutter flow rates and inlet interception efficiencies, the 33% increase in flow presented to Inlet No. 4 will overtax the capacity of the structure, causing the roadway sag to flood. If the ponded

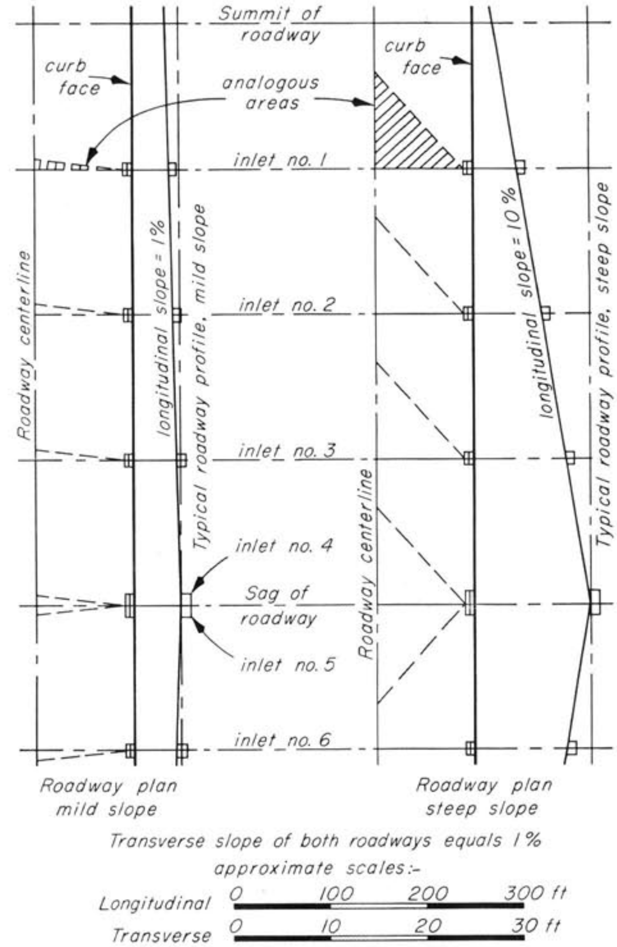


Fig. 2. Inlet Drainage Areas for Mild and Steep Highway Slopes

depth is sufficient to flood over the gutter curbing or shoulder, serious damage to adjacent property could result.

The foregoing discussion has been limited to uniform pavement grades without vertical curves at either the summit or the sag. The effect of a vertical curve at the roadway sag is to aggravate the flooding because of the reduced grade near the sag. Storm water flowing down the steep gutter will move with high velocity and minimum cross-sectional area and depth. Upon encountering the reduced gradient of the vertical curve, the flow must expand to compensate for the reduced velocity. The expansion will cause an increased depth and width of flow, and while a greater volume of water will be stored above the pavement, it will be moving more slowly, thus enlarging the flooded area.

7. The Approach Gutter

The flow rate capacity and the velocity of flow of the approach gutter are of particular importance in the design of a gutter inlet system. Since the flow rate capacity of the gutter is the product of the velocity and the cross-sectional area, only the gutter flow rate is discussed in this section. Velocity will be discussed in Section 9.

The hydraulic capacity of the gutter is dependent upon its longitudinal gutter slope, cross-sectional area, the physical roughness of the surface, and the depth of flow.

The longitudinal gutter slope is usually assumed to be the primary variable affecting the discharge rate. The Manning equation to determine the gutter capacity is

$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2} \tag{3}$$

where Q is the discharge rate, cfs, A is the cross-sectional area of flow, sq ft, R is the hydraulic radius, ft (equal to the area divided by the wetted perimeter), n is the physical roughness coefficient, and S is the longitudinal slope of the water surface, ft per ft. Factors A and R are both functions of the gutter shape, and for any gutter are explicit with d, the flow depth. The longitudinal slope of the water surface, S, is usually assumed to be equal to the slope of the gutter invert, *i.e.* the flow is uniform, and the two slopes are parallel. This assumption is slightly in error, particularly for gutters with little cross slope. The error is caused by the lack of steady flow conditions in the gutter channel. The gutter receives water from the roadway pavement throughout its length, resulting in an unequal rate of flow at any two points. Therefore, the flow can never be theoretically steady or uniform. The incremental addition of pavement flow to the gutter has two effects on the flow already in the gutter. Most important, the depth and width of flow are constantly increasing. Second, runoff from the pavement must change its direction of flow upon entering the gutter. This action consumes a small part of the kinetic energy present in the gutter flow. Since there is no practical justification for a varied flow calculation, and because the designer is usually only interested in the maximum gutter capacity, the error induced by the uniform flow equation is acceptable.

The fact that the depth and width of flow in the gutter are constantly increasing in the direction of movement is of considerable importance from both the operational and design aspects, if not from the energy of flow view point. Most inlet grates are only as wide as the gutters in which they are installed. Therefore, the flow interception at the inlet is usually limited to the flow that is actually in the gutter prism. Only a small amount of pavement water is intercepted by the usual gutter inlet grate.

Figure 1 indicates the geometrical pattern of flow that should be expected in a gutter adjacent to the roadway pavement. The dashed line, $xyzb'$, represents the edge of the gutter flow, or line of encroachment on the pavement side, when the upstream inlet operates with nearly 100% efficiency. The width and depth of flow just below Inlet A is, for practical purposes, zero. From this point downstream both the width and depth of flow increase due to the addition of runoff from the pavement drainage area.

The shape of the encroachment line is interesting since it illustrates the importance of gutter flow width and depth. At point x, in the gutter just below Inlet A on Fig. 1, the rate of gutter flow is zero when Inlet A operates with 100% efficiency. Because of the triangular gutter shape, the gutter encroachment line from x to y is a long curve, concave toward the curb face. When runoff is added near x, the flow section must widen appreciably to provide the required flow area. Conversely, when the same rate of runoff is added just upstream from y, the flow width will change only slightly since most of the required flow area will be provided above the existing water prism. This characteristic of gutter flow is illustrated in the two side sketches in Fig. 1. The shaded areas in the two gutter sections are equal and represent 0.14 sq ft.

At point y on the roadway plan in Fig. 1, the slope of the encroachment line increases rapidly with respect to the curb face. This sudden change in shape is due to the water now moving on the pavement. Since the cross slope of the pavement is very mild, a small increase in gutter depth will cause a large increase in pavement encroachment. The flow will continue to expand onto the roadway until reaching z, where the influence of inlet interception will be reflected by a rapid decrease in width of encroachment. Finally, if Inlet B operates with 100% efficiency, the pavement encroachment becomes zero at point b' opposite the downstream end of Inlet B.

Because the inlet can intercept only a small amount of water from the pavement surface, for any given cross section, encroachment is the by-product of the increased volume of flow in the gutter prism. It is a direct function of the difference between the gutter depth and the total fall across the flag, or horizontal surface, of the gutter.

Table 2 has been prepared, in accordance with Eq. 3, to illustrate the large increase in gutter capacity that occurs when roadway encroachment is permitted. The encroachment width shown in the last column of the table are based on a pavement cross slope of 2%. The gutter shape used in the preparation of the tabular data is shown in Fig. 1, and the coefficient of gutter roughness has been assumed to be 0.015. The table pertains only to flow in the gutter prism and does not include pavement flow.

Table 2 shows, for the section used in the example, the rate of flow within the gutter prism may be increased by 194% if the depth is allowed to rise 0.2 ft above the full gutter stage and to cause a pavement encroachment of 10 ft. However, there is a limit to the amount of pavement encroachment that may be tolerated from the standpoint of traffic safety. It is impractical to allow water to stand across three-fourths of the roadway just upstream from every inlet.

There is also a hydraulic limitation to the amount of pavement encroachment that is desirable. At any installation, large encroachment widths indicate large quantities of flow that will move past the gutter inlet on the pavement surface. The flow bypassing the inlet is usually called carryover flow.

Table 2

Hydraulic Capacity of a Triangular Gutter

Longitudinal Slope = 1.0%

Flow Depth	Flow Area	Wetted Perimeter	Hydraulic Radius	Flow Capacity	Incremental Increase	Pavement Encroachment
ft	ft^2	ft	ft	ft^3/sec	ft^3/sec	ft
0.1	0.02	0.51	0.039	0.023	0.00	0.0
0.2	0.08	1.02	0.078	0.145	0.122	0.0
0.3	0.18	1.54	0.117	0.427	0.282	0.0
0.4	0.32	2.05	0.156	0.922	0.485	0.0
0.5	0.50	2.56	0.195	1.66	0.738	0.0
0.6	0.72	2.66	0.271	2.99	1.33	5.0
0.7	0.98	2.76	0.355	4.87	1.88	10.0
0.8	1.28	2.86	0.447	7.40	2.53	12.0*

* Water 0.06 ft deep at centerline of 24-ft, symmetrical crown roadway.

The solid flow line in Fig. 1 indicates the encroachment that is caused by carryover from Inlet A. This line is similar to line $xyzb'$, except that it is displaced toward the roadway centerline. The distance between the two lines of encroachment is a function of the carryover rate and varies from point to point along the gutter because of the changing flow section.

The hydraulic limitation on allowable carryover becomes important when the total allowable roadway encroachment is a specified distance. For the purposes of this discussion assume that the allowable encroachment is equal to the encroachment at Inlet B when Inlet A is 100% efficient. To satisfy this requirement when there is carryover from Inlet A it is necessary to move the lower inlet upstream to point z'. The physical distance that it is necessary to move the inlet is an inverse function of the roadway cross-slope and a direct function of the carryover rate. Obviously, any movement of Inlet B toward Inlet A will decrease the inlet interval and increase the number of inlets required in a fixed total distance.

However, the tolerance of reasonable pavement encroachment will considerably increase the efficiency of the drainage system. The occurrence of pavement flow will also be greater. An example illustrating the effect of carryover on an inlet series is included in Section 25 of this report.

8. The Subsurface System

The design of subsurface drainage systems is a topic of sufficient scope and complexity to justify a separate report. The purpose of this discussion is to outline the influence of the subsurface system upon the interception efficiency of gutter inlet grates.

Most inlet grate designs are based upon the assumption of rapid removal of the accumulated gutter flow. In the usual design, water falls through the inlet grate into either a catch basin or inlet box structure. Water ponds in this structure until the head on the subsurface drainage pipe is sufficient to cause the outflow to equal the inflow. This ponding action causes the loss of most of the kinetic energy in the falling water. Considerable work has been done recently in developing a subsurface structure that does not waste the kinetic energy of the falling water, thus eliminating, to a large degree, the ponded water beneath the inlet grate.[3] Utilization of this energy is not important to the inlet grate efficiency except for the way that the ponded water affects the grate interception characteristics.

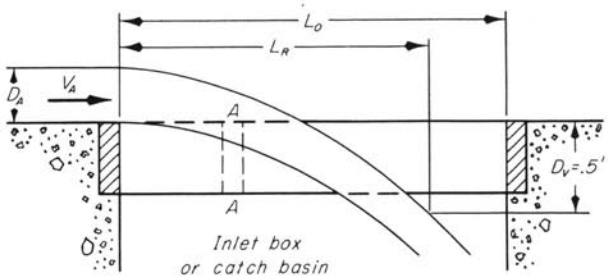
The inflowing jet is deflected by the water in the inlet structure when flow passes through the inlet grate and directly into the ponded water. The deflection is always toward the downstream end of the inlet grate. When the velocity in the approach gutter is great and the ponded water is close to the bottom of the grate, the inflow jet tends to skip over the ponded surface and bounce out of the inlet. This is the most serious form of grate inefficiency that is caused by insufficient capacity in the subsurface system.

The second type of action occurs in shallow basins beneath grates serving lower gutter velocities. In this case the jet moving into the ponded volume establishes a vertical circulation within the inlet box. The effect of the circulation current is to lift the gutter flow at a point just downstream from the overfall, and cause the jet to overshoot the inlet opening.

The action that usually occurs at a flooded inlet is not as spectacular as the two preceding cases. When the approach velocity is low, the jet falls into ponded water within the upstream portion of the inlet grate length. If the discharge pipe cannot handle the inflow volume, water boils upward and out of the grate in the downstream portion of the inlet grate opening.

Each of these patterns is dangerous. The first two cases may cause trouble because of jet deflection over the curbing or onto an unpaved surface. All three patterns are dangerous because the inlet cannot intercept the design quota of storm water runoff. This insufficiency overloads the downstream inlets, and the trouble becomes cumulative along the entire system.

Movement of the water from the downstream end of the inlet into the gutter will pass additional debris to the inlets downgrade. Debris that has been screened from the subsurface system by the



D_A = depth of flow in approach gutter, ft
L_O = length of bar opening, ft
L_R = required length of opening, ft
V_A = velocity of flow in approach gutter, fps

Fig. 3. Flow Between Bars of Parallel Bar Inlet Grate

inlet grate is usually deposited at the downstream end of the grating. When the subsurface system cannot adequately handle the intercepted flow and water flows from the basin to the gutter, the lodged material is flushed into the downstream gutter. This action imposes an additional debris load on the next inlet grate in the gutter system.

9. The Inlet Grate

Three inlet grate characteristics are of primary importance in determining the interception efficiency of the installation. These are the geometrical pattern of the grate, the amount of flow-through area presented to the gutter flow, and the ability of the grate to properly handle detritus and floating trash.

The functions of the geometrical pattern of the grate and the flow-through area are interwoven and, to a large extent, dependent upon each other. Moreover, the importance of both functions stems from the path of water falling through the grating and the kinematics of the water particles that comprise the intercepted flow.

Figure 3 shows the mechanics of flow through an inlet grate. For discussion purposes, the grate is assumed to be composed of bars parallel to the curb face and two end bars. There are no transverse bars in the flow area. Figure 3 depicts flow through any one of the openings between the parallel bars.

One basic concept must be established before proceeding with a discussion of the mechanics of the falling sheet of water. It is apparent that when the required length of grate opening L_R is equal to or greater than the actual length of opening L_O, the inlet cannot operate with 100% efficiency. In similar fashion, it should be understood that for 100% interception, L_R must be less than L_O by an amount sufficient to drop the free-falling jet, or nappe, the vertical distance D_V. The vertical distance, D_V, is defined as the distance necessary to prevent splash, at the point of nappe impact with the downstream wall, from moving upward out of the inlet and into the downstream gutter. With this concept established, it is possible to develop a simple explanation of flow through the grating.

It is assumed that water reaches the inlet grate in an approach gutter with velocity V_A, and depth D_A. Based upon the 100% interception concept of the foregoing paragraph, it is apparent that for complete interception a particle on the water surface must fall a distance equal to the sum of D_A and D_V. The length of grate opening required to accomplish this drop may be found by application of the free-body equation.

In general form the equation of a freely falling body is

$$y = \frac{1}{2} g t_v^2 \tag{4}$$

where y is the drop distance in ft, t_v is the drop time in sec, and g is the acceleration due to gravity with ft/sec^2 dimensions.

Equation 4 may be transposed to the following form:

$$t_v = (2y/g)^{1/2} \tag{5}$$

Considering the approach gutter velocity, it is apparent that the following expression may be written

$$L_O = V_A t_H \tag{6}$$

where L_O is the opening length, ft, V_A is the velocity of approach, fps, and t_H, in sec, is the time required for a water particle to move across the inlet opening.

Equation 6 may be written as

$$t_H = L_O / V_A \tag{7}$$

Since the time available for the water to drop into the opening is equal to the time of translation, t_H, Eqs. 5 and 7 may be equated to each other.

$$\frac{L_O}{V_A} = t_H = t_v = \left[\frac{2y}{g}\right]^{1/2}$$

and solving for the length of opening

$$L_O = V_A \left[\frac{2y}{g}\right]^{1/2} \tag{8}$$

Equation 8 is in the general form for determining the length of opening required to allow a particle moving with a translative velocity, V_A, to fall a vertical distance, y. This equation may be used to determine the required length of grate opening, L_R. Since L_R is the length required to allow the nappe to fall through the distance $D_A + D_V$, Eq. 8 becomes:

$$L_R = V_A \left[\frac{2 (D_A + D_V)}{g}\right]^{1/2} \tag{9}$$

With certain qualifying assumptions, Eq. 9 can yield an expression for the required length of grate opening in terms of the rate of flow in the approach gutter. It must be understood that the following development applies only to the particular case of a triangular approach gutter with vertical curb, and that the solution is approximate because of the assumptions made. Its purpose is to illustrate the mechanics of inlet grate operation.

Equation 9 may be expanded to

$$g L_R^2 = 2 V_A^2 D_A + 2 V_A^2 D_V$$

With the assumption that D_V must be 6 in. to avoid back splash the expansion becomes

$$g L_R^2 = 2 V_A^2 D_A + V_A^2 \tag{10}$$

With the assumption that the gutter is of triangular section with vertical curb face, and ignoring the question of velocity distribution within the flow prism, the following expression denotes the total rate of flow when the gutter is full.

$$Q = A V_A = 0.5 W D_A' V_A \tag{11}$$

where Q is the gutter flow rate, cfs, W is the gutter width, ft, D_A' is the depth at the curb face, ft, and V_A is the mean gutter velocity. If the gutter width is 24 in. and the gutter cross fall is 6 in. Eq. 11 becomes,

$$Q = 0.5 V_A \tag{12}$$

or

$$V_A = 2Q \tag{13}$$

This expression may be combined with Eq. 10 to give the following specific relationship.

$$L_R = \sqrt{\frac{8}{g}}\, Q \tag{14}$$

Since D_A' is the maximum depth in the approach section, the opening, L_R, is the maximum length of opening required to accommodate the flow.

Equation 14 assumes that the width of inlet bar is small in comparison with the width of opening

Table 3

Required Opening Length for Inlet Grate Serving Triangular Gutter

Pavement Slope %	Pavement Slope ft/ft	Flow Depth ft	Flow Velocity ft/sec	Flow Rate ft^3/sec	Opening Length ft
0.25	0.0025	0.50	1.66	0.83	0.41
0.50	0.005	0.50	2.36	1.18	0.59
1.00	0.010	0.50	3.32	1.66	0.83
2.00	0.020	0.50	4.64	2.32	1.15
4.00	0.040	0.50	6.64	3.32	1.65
6.00	0.060	0.50	7.96	3.98	1.98

between the bars. More will be said about this limitation later.

Based upon Eq. 14, Table 3 has been prepared to show the relationship between opening length and longitudinal gutter slope. The table applies only to a triangular gutter 2 ft wide, with vertical curb face, and 0.5 ft of cross fall. The last column of the table is a listing of the theoretical length of inlet grate that is required to intercept all of the flow in the approach gutter.

The theoretical analysis is a much simplified version of the line of reasoning that is being applied to the mechanics of flow through inlet grates. The designer can expect a fairly complete physical analysis of the interception action within the next few years. Some problems that complicate the more exact analysis are velocity distribution, influence of bar width, and gutter slope not perpendicular to the line of gravitational attraction. Each of these factors has the effect of making the physical grate length less than the required length. The factors that have the effect of making the physical length greater than the required length include drawdown in the approach gutter immediately upstream from the inlet, roughness of the grate bars, and depth of the grate bars. Consideration of flow on the pavement surface further complicates the analysis and immediately involves the question of velocity distribution in the approach gutter. It is anticipated that all of these problems can be analyzed physically so that a comprehensive theory may be developed.

This development has been presented for two reasons. First, because a brief outline of the theoretical analysis is of interest to the design engineer, and, more important, because the simple theory serves as a base point for discussion of the geometrical pattern and the flow-through-area features of an inlet grate.

The theory shows that one of the essential factors for efficient grate operation is length of the opening. Table 3 indicates that the opening length is most critical for high gutter velocities. The use of inlet grates with transverse bars, other than end bars, conflicts directly with the requirements of the free fall theory. Reference to Fig. 3 shows that the insertion of a transverse bar at *A-A* will insure the interception of most of the flow that is already below the top of the bar. However, the width of the transverse bar will reflect the falling nappe in an upward direction, thus decreasing the effective opening of the grating. This is of the greatest consequence, as the inclusion of transverse bars may cause as much as a 100% increase in the required length of the inlet grate.

Another essential factor for efficient grate operation is the percentage of the total grate width that is open just downstream from the upstream end bar. This is usually expressed as the ratio of bar width to opening between the bars. It might better be defined as the ratio of total width of openings to total width of bars. Inlet grates with small bar-width to bar-opening ratios will be most efficient. This criterion applies particularly to installations serving gutters with high flow velocities. When the approach velocity is low, or when the inlet is submerged by ponded water, the bar-width to bar-opening ratio becomes relatively unimportant. In this case the controlling ratio is the open surface area of the grating divided by the plan area of the entire grating. Large values of this ratio, with a maximum of 1.0, will result in most efficient operation.

When inlet grates are used in conjunction with curb opening inlets, it might be necessary to have the bars deflect the gutter flow into the curb opening. Excellent work was completed on this subject by Larson[7] at the University of Minnesota. However, the designer is cautioned that curb opening inlets will not screen the flow as effectively as inlet grates. There is little advantage in the use of an inlet grate if the flow does not need to be screened.

The ability of an inlet grate to effectively handle the detritus and floating debris entrained in the gutter flow is very important. Since the primary function of the grate is to remove objectionable material from the intercepted flow, it must be considered inadequate if it is unable to perform this function. Almost any grate pattern will intercept flows of clear water moving with low velocity. The fact that storm runoff is seldom composed of clear water requires that the structure be capable of efficient debris separation.

Gutter debris is usually composed of detritus, such as dirt, sand, stones, and cinders, or of floating trash such as small tree branches, leaves, paper, tin cans, and similar highway litter. Usually storm water carries both types of material.

In most cases the removal of detritus is not considered a function of the inlet grate. This material is usually removed in a catch basin type of structure, or is allowed to pass through the system. The controlling requirement in this case is the sediment-carrying capacity of the subsurface system. The velocity of flow in the drainage pipe is usually greater than the velocity in the gutter served by the pipe. When this condition prevails, small detritus does not need to be separated from the flow, since it cannot deposit in the drain pipe.

High-capacity gutters can bring stones 2 or 3-in. in diameter, or larger, to the inlet. This size material should be eliminated from the flow regardless of the slope of the drain pipe. Material of this size moves at a much lower velocity than the water in which it is entrained. Therefore, the maximum runoff rate in the gutter at the peak of the storm could carry the material into the storm drains only to be deposited when the flow rate diminishes. Later, smaller flow rates would deposit the smaller sedimentary material in the vicinity of the large stone, or stones, and a serious obstruction would develop. Another factor to be considered in the passage of large detritus is that of erosion. Large materials moving through the sewer will abrade and chip the pipe invert much more rapidly than the smaller materials.

Floating trash is a far more serious problem than that of detritus. This is primarily due to the great effect that floating trash has upon the interception efficiency of the inlet grate. This is not true of the usual roadway detritus.

Almost all inlet grate systems must be protected from excessive floating trash loads. This protection may be provided by controlled planting on the drainage area or a systematic program of street sweeping. In urban areas, where inlet grate systems are extensive, the best protection from trash overload is the street sweeping program, whereas in rural areas, or on limited access roadways, the best protection from trash overload is a controlled planting program. This program eliminates large-leaf trees and bushes, and limits the planting of twig producing trees or shrubs to grassed areas where the objectionable materials cannot be carried, bv water or wind, into the roadway gutter. Regardless of these measures, periodic cleaning of inlet grates cannot be avoided. If the inlet grate performs its trash separation function, material will accumulate either on the grate itself or in the gutter just downstream from the grate.

Laboratory and field tests have conclusively demonstrated that inlet grates composed of parallel bars are better able to handle trash than grates with transverse bars. The greatest portion of floating trash will reach the inlet grate early in the runoff period. The trash separation action of a parallel bar grate is as follows. Large material is screened from the flow and lodges on the surface of the bars as storm water passes between the bars of the inlet grate. As the rate of flow increases, the depth and velocity of flow in the approach gutter also must increase. This requires an increase in the effective length of the opening. As the effective length of grate opening increases, to accommodate the greater depth and velocity, the storm water tends to push the accumulated trash to the downstream end of the inlet. In this way the parallel bar inlet is partially self-cleaning. This type of action cannot occur when the grate has transverse bars since the trash lodges against them. In this case, as the rate of flow increases, greater pressures occur and the trash becomes more and more firmly lodged in place. Additional trash from the gutter accumulates on the transverse bars and the effective opening for flow interception decreases. Eventually, the entire grating becomes covered with trash and ceases to function as a gutter inlet. The reader can observe this action on inlets in his own locality after a windy rainstorm. Trash will accumulate at the upstream end of inlets with transverse bars, and at the downstream end of inlets with parallel bars. It will also be noted that smooth parallel bars have better cleaning characteristics than rough parallel bars. As the bar smoothness increases, the self-cleaning ability also increases.

Completely self-cleaning model inlet grates have been tested in the laboratory. This is done by allowing the storm water to fall between the bars a short distance upstream from the opening beneath the grate and by making the actual length of grate opening slightly less than the required length. Two specific effects can be noted. Allowing the flow to fall between the bars upstream from the inlet opening causes an increased horizontal velocity between the bars and thus material is carried to the downstream end of the grate more effectively. The fact that the actual grate opening length is slightly less than the required opening length causes the falling nappe to strike the downstream side of the inlet just beneath the accumulated trash. The impact of the flow jet on the vertical wall causes splash to move vertically out of the inlet. The splash flow washes the trash off the inlet, depositing it in the gutter just downstream. This self-cleaning action is mentioned only as a matter of interest. It is dependent upon an exact design for particular velocity of approach, which eliminates it from practical use.

The preceding discussion regarding the interception of flow by inlet grates has considered only the flow in the approach gutter since most of the intercepted flow originates there. However, when the gutter is on a flat longitudinal slope, a significant amount of additional water may be intercepted. At the upstream end of the grate, this additional flow is on the pavement. As shown at Inlet A of Fig. 1, when the longitudinal gradient is mild, some storm water will enter the inlet from the pavement and the downstream gutter.

After the water in the gutter prism has entered the inlet, water on the pavement tends to move toward the curb face. This is indicated by the flow arrows at Inlet A of Fig. 1. A part of this water will be intercepted at the side of the inlet grate in a manner similar to a curb opening inlet. This flow will be largest at the upstream end of the inlet and will diminish toward the downstream end. More flow can be intercepted by lengthening the inlet. The portion of the pavement flow not intercepted in this manner will flow into the downstream gutter.

Water passing the side of the inlet will accumulate in the downstream gutter prism. The depth at this point must increase until it satisfies the friction slope requirements of the downstream gutter. This accumulation of water will cause a portion of the flow to move upstream in the gutter and enter the inlet grate from the downstream end.

Summarizing these two actions, it may be said that when the longitudinal gutter slope is greater than about 0.5%, the amount of flow intercepted at the downstream end will be relatively small. When the slope is less than 0.5%, it may be appreciable, depending upon both the slope and shape of downstream gutter. The amount of water that enters the inlet grate from the pavement side depends upon the flow velocity and the length of inlet grate. When the velocity is low and the grate is long, this interception may also be large.

IV. CALIBRATION OF STANDARD INLET GRATES

In 1953, the Illinois Division of Highways revised the specifications of all standard gutter inlet grates used in new construction to eliminate the use of transverse bars in the inlet grate castings. Parallel bar designs, which possessed the same structural strength as the "checkerboard" grate patterns were developed for all standard inlet openings. This was usually accomplished by gradually increasing the depth of the individual parallel bars from a minimum at the ends of the grate to a maximum at mid-span. Since the new grate had to be interchangeable with the old standard, the depth of bar at the ends of the grate was not changed, and all bearing bars were maintained at standard depth. The hydraulic efficiency of the grating was increased and the casting simplified when transverse bars were eliminated. In most cases, the parallel bar grate was lighter in weight than the comparable "checkerboard" grate.

Although based on hydraulic model information, the new grate designs were not hydraulically rated as to capacity. The standard grates are of cast iron construction while the model program considered a protected steel grating. As a result, the final standard cast iron design compromised the indications of the hydraulic model investigations.

The purpose of the experimental portion of this study was the development of hydraulic rating curves for several of the standard inlet grate designs.

10. Experimental Apparatus

Early discussions regarding the inlet grate calibration work revealed that over 80% of the grates employed by the Illinois Division of Highways were used in barrier curb gutters or in "V"-type gutters. Because the standard design included two widths for each type of gutter, it was decided to conduct tests using four gutter sections.

Each of the gutter and inlet grate sections had to be tested throughout a wide range of longitudinal slopes to provide data for various approach velocities. The slopes tested in the model varied from 0.125 to 6.0%.

It was decided that the test apparatus should include only the inlet frame and grate with appropriate entrance and exit channels. Pavement sections and small sections of the gutter were not included in the laboratory apparatus. This decision was based upon two facts. Prior laboratory studies indicated that most of the flow intercepted by an inlet grate originates in the gutter flow prism. Also, traffic usually limits the volume of water that may be carried on the pavement because of encroachment difficulties, making the pavement flow small compared to the total gutter flow.

Elimination of the pavement section from the test program allowed the development of simple and inexpensive test procedures. Since the maximum flow that could occur in the prototype gutter was within the laboratory pumping capacity, it was possible to construct full scale test apparatus. This procedure allowed the use of actual inlet frames and grates rather than scale models. The savings inherent in this procedure, particularly with reference to the curb opening inlets, more than offset the additional cost of the larger gutter and support frame.

Four removable gutter channels and a channel support structure were the major apparatus constructed in the laboratory. The support structure was designed so that gutter channels, inlet frames, grates, and carryover flow sections could be changed with a minimum of effort.

The gutter support structure was designed as a continuous truss with two points of support. The support at the upstream end of the truss was a section of 6-in. diam pipe 4.2 ft long. The pipe was installed transverse to the model and served as a pivot for rotation of the truss when the slope of the channel was changed. The load from the truss was carried into the pipe by short lengths of 6-in. channel steel to prevent timber bearing failure at the point of support. The downstream truss support was located just upstream from the inlet grate test section. Bearing at this point was provided by interchangeable temporary wood frames built to accommodate major changes in longitudinal slope.

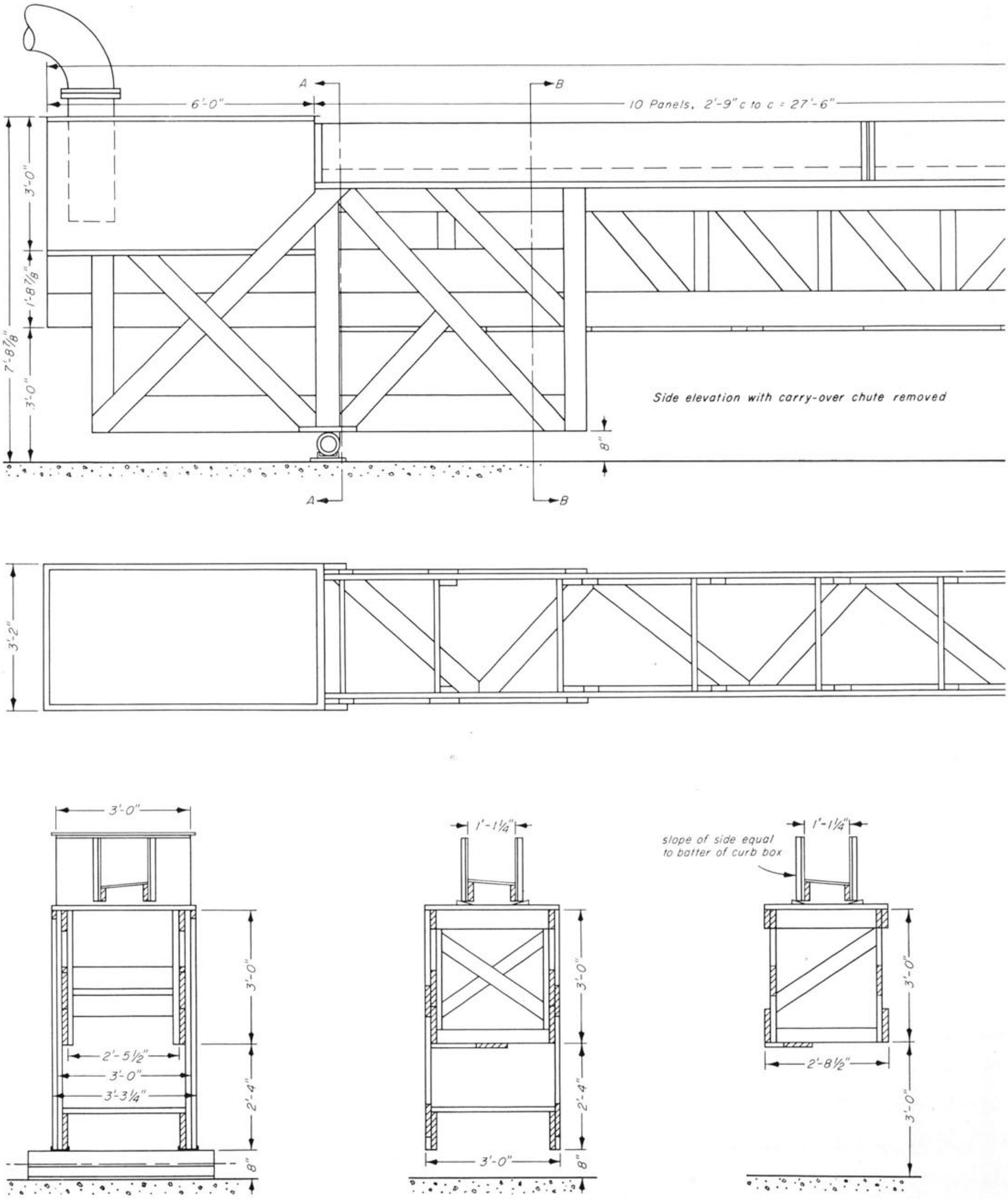


Fig. 4a. Test Channel and Support Truss

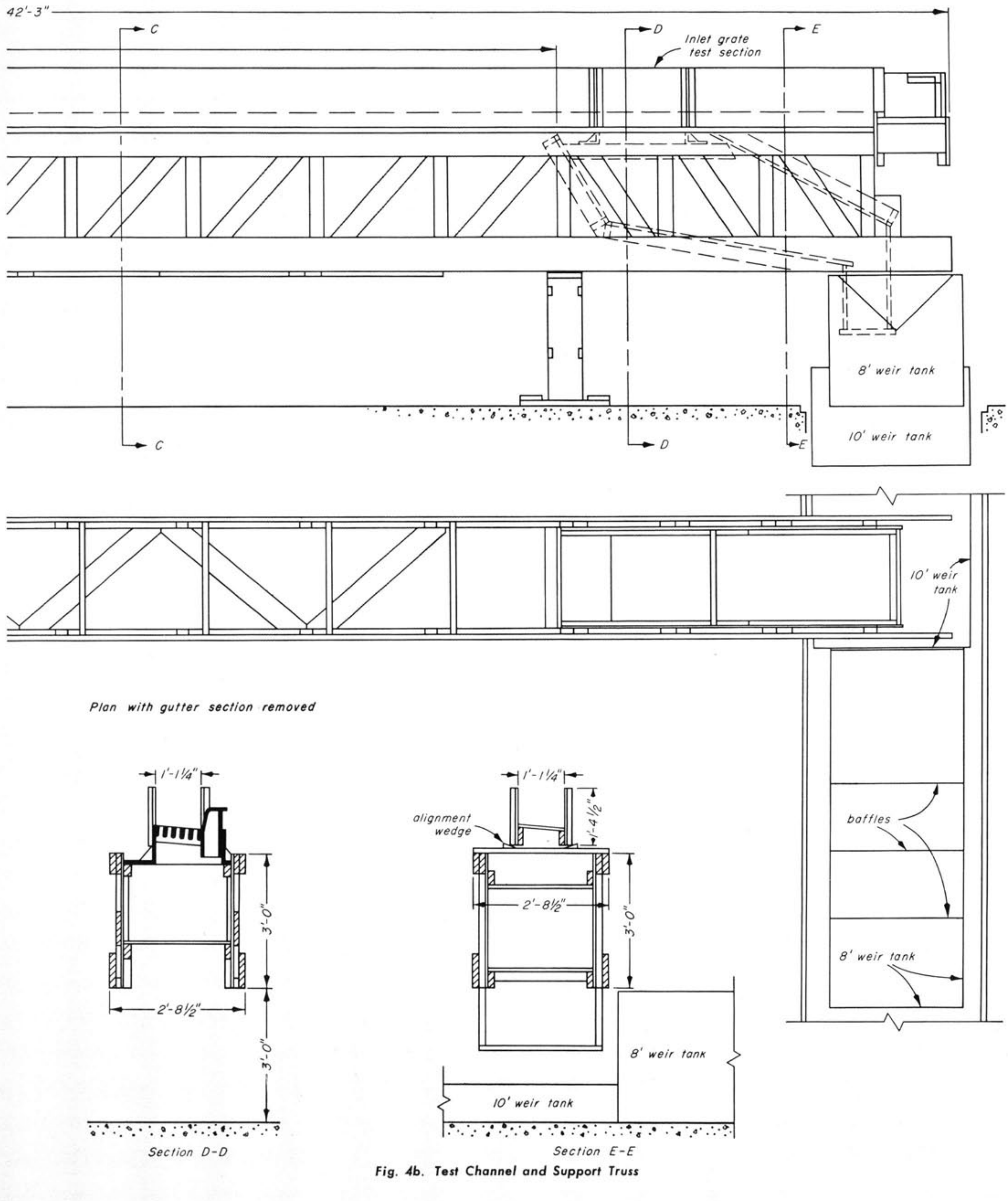


Fig. 4b. Test Channel and Support Truss

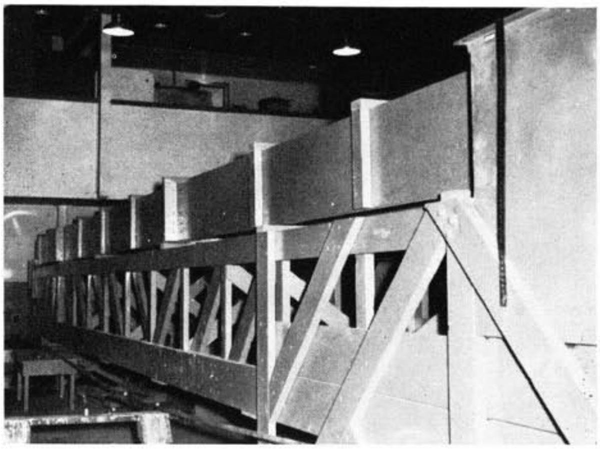


Fig. 5. Model Support Frame

Wooden wedges and spacer blocks were placed between the lower chord of the truss and the top of the wood frames to provide for precise slope adjustment. The load reaction at the downstream support was always positive but was small because of the carryover loading at the upstream support. Details of the support structure are shown in Fig. 4. Figure 5 is a side view of the channel support structure and indicates the use of the channel support wedges.

Four separate gutter sections were built, each to the dimensions of their respective inlet grate frames. The dimensions and details of the gutter sections are shown in Fig. 6. Each of the approach gutter sections was 28 ft long. A carryover gutter section was used downstream from the inlet test area. The total length of approach gutter, inlet, and carryover gutter was 34.6 ft in all cases.

Each gutter channel was composed of four sections. Installation of gutter sections on the support frame was accomplished by placing the upstream section and bolting it to the entrance tank. Each

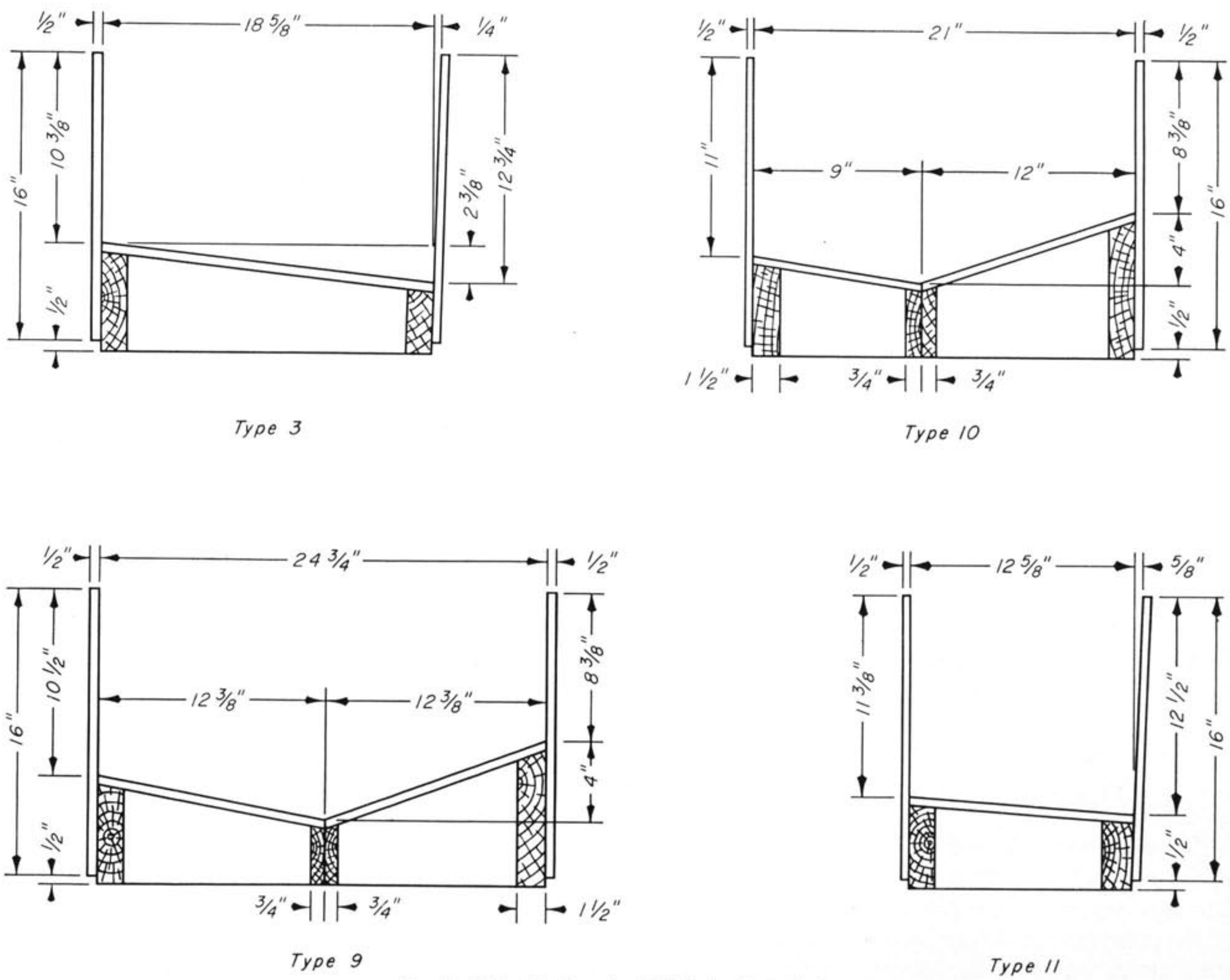


Fig. 6. Gutter Sections for Full Scale Grate Tests

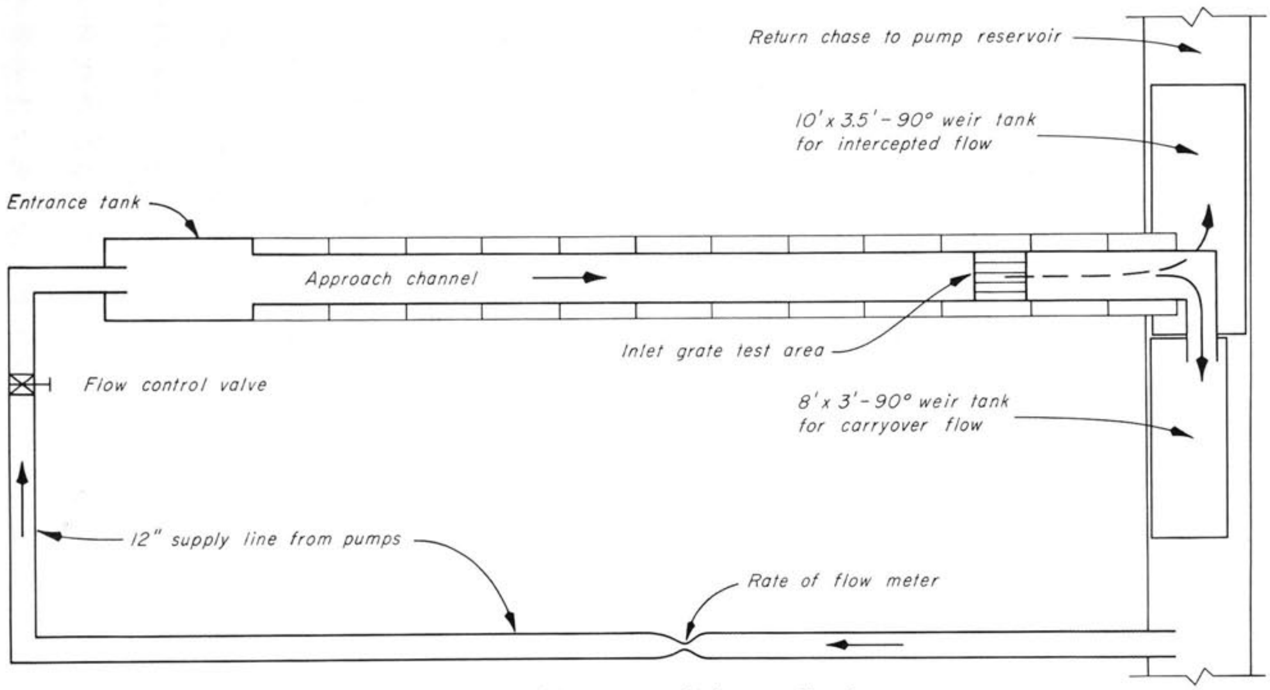


Fig. 7. Diagram of Apparatus and Laboratory Flow System

additional section was installed and bolted to the preceding section until the test area was reached. The inlet frame was then bolted to the end of the approach gutter, and, finally, the carryover gutter was installed.

After the entire test channel was in place on the support truss, the gutter was carefully set to grade. Small wood wedges were used between the bottom of the gutter and top of the truss to permit accurate alignment. Tensioning devices, composed of aircraft control cable and turnbuckles, were used to place the wedges under compression, locking the gutter to the support frame. The gutter invert slope was then rechecked. Insertion of the inlet grate made the apparatus ready for test.

As shown on Fig. 4, a special plywood channel was installed between the two sides of the support structure to carry water intercepted by the inlet grate to one of the measuring weir tanks. A permanent chute, attached to the downstream end of the support frame, carried flow from the carryover gutter to a second measuring weir.

11. Water Supply

Water was pumped to the test apparatus from the laboratory reservoir through a 12-in. diam pipeline. Since the flow rates exceeded the capacity of the constant head tank, all tests were conducted with direct pumping to the entrance tank located on the gutter support structure. To avoid surges and flow fluctuations, no test runs were made with the supply pump operating at more than about 60% of capacity. When the flow rate from a pump reached 60% of its capacity, it was replaced by a higher capacity unit. Therefore, nearly all tests were performed using the 2,400 GPM deep well turbine unit.

Water flowed from the entrance tank on the support structure into the approach gutter channel, and then to the inlet test area. The portion of the flow that was intercepted by the inlet grate passed through the plywood chute in the support truss to the measuring weir. After flowing over the weir, the water spilled into the subfloor chase and returned to the pump reservoir. The portion of the gutter flow not intercepted by the inlet grate flowed down the carryover channel, through a chute at the end of the support frame, into the second weir tank, then into the subfloor chase.

A schematic diagram of the laboratory apparatus and water flow path is shown in Fig. 7. Figure 8 shows water flowing through one of the test channels, and the location of the two weir tanks.

12. Instrumentation

Three types of measurements were taken during the tests. Point gages were used to obtain flow

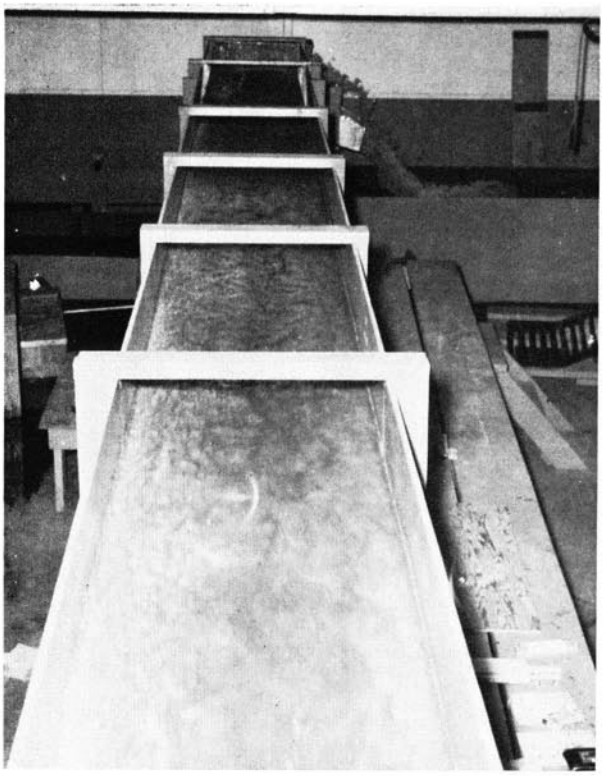


Fig. 8. Test Channel

profiles in the gutter, component flow rates were determined, and the pattern of flow through the inlet grate was recorded.

Seven point gages were used on each of the approach gutter channels. The downstream gage, No. 7, was located at the point of overfall into the inlet opening. The other six gages, uniformly spaced about 4 ft apart upstream, were used to determine the general profile of flow in the approach gutter. In addition, auxiliary gages were necessary to determine the drawdown curve at the inlet and to measure the depth of flow in the carry-over gutter.

Two methods were employed to determine the rate at which water was supplied to the test channel.

When the rate was low, the total flow was determined by summation of the outflow weir measurements. Flow that was intercepted by the inlet structure was measured with a 90° stainless steel V-notch weir mounted in the end of a $3.5 \times 10.0 \times 3.5$ ft deep, baffled weir tank which had a maximum capacity of 3.0 cfs. Flow not intercepted by the inlet was measured in a $3.0 \times 8.0 \times 3.0$ ft deep weir tank (1.5 cfs capacity) also equipped with a 90° V-notch weir plate. When neither of the component flows exceeded the capacity of the respective weirs, total flow was determined by adding the two measured flows.

When either of the component flow rates exceeded the accurate capacity of its weir tank, the total flow was determined by use of a Sparling venturi-propeller-type meter, with an accurate range of 2.5 to 9.0 cfs, located in the 12 in. supply line. Since the meter could measure flows well under the capacity of the combined weir tanks, there was ample overlap in the two types of flow determination. When the apparatus was operated in the overlap range, flow was determined by both procedures to check the stability of the meter apparatus and the weir measurements.

Detailed measurements were made of the pattern of flow through the inlet grate. For each run, the effective length of the opening between inlet grate bars was determined. In some cases the rate of flow over an individual grate bar was also determined.

In addition to the data described, photographs were taken of all tests that exhibited unusual flow characteristics. In certain cases, gutter velocities were measured with a midget current meter to aid in the analysis of the inlet flow pattern.

13. Experimental Procedure

Flow was introduced to the channel, and the system was allowed to come to equilibrium. Equilibrium was determined by the constancy of reading on the two weir tank hook gages.

After achieving equilibrium, the point gages on the approach channel were read and the values recorded. Dimensional measurements were then made of the pattern of flow into the inlet grate and a photograph was taken of the inlet grate test area. The weir tank gages were read, and if the readings were the same as those obtained at the beginning of the test, they were recorded, completing the test run.

The number of test flow rates was determined by the characteristics of each inlet. For example, the minimum flow rate tested was the highest rate that the inlet could handle with 100% interception, and the maximum flow tested was determined by the capacity of the approach channel. Intermediate runs were made when the gutter depth was equal to the gutter cross fall, when the flow was just impinging on transverse bars of the "checkerboard"

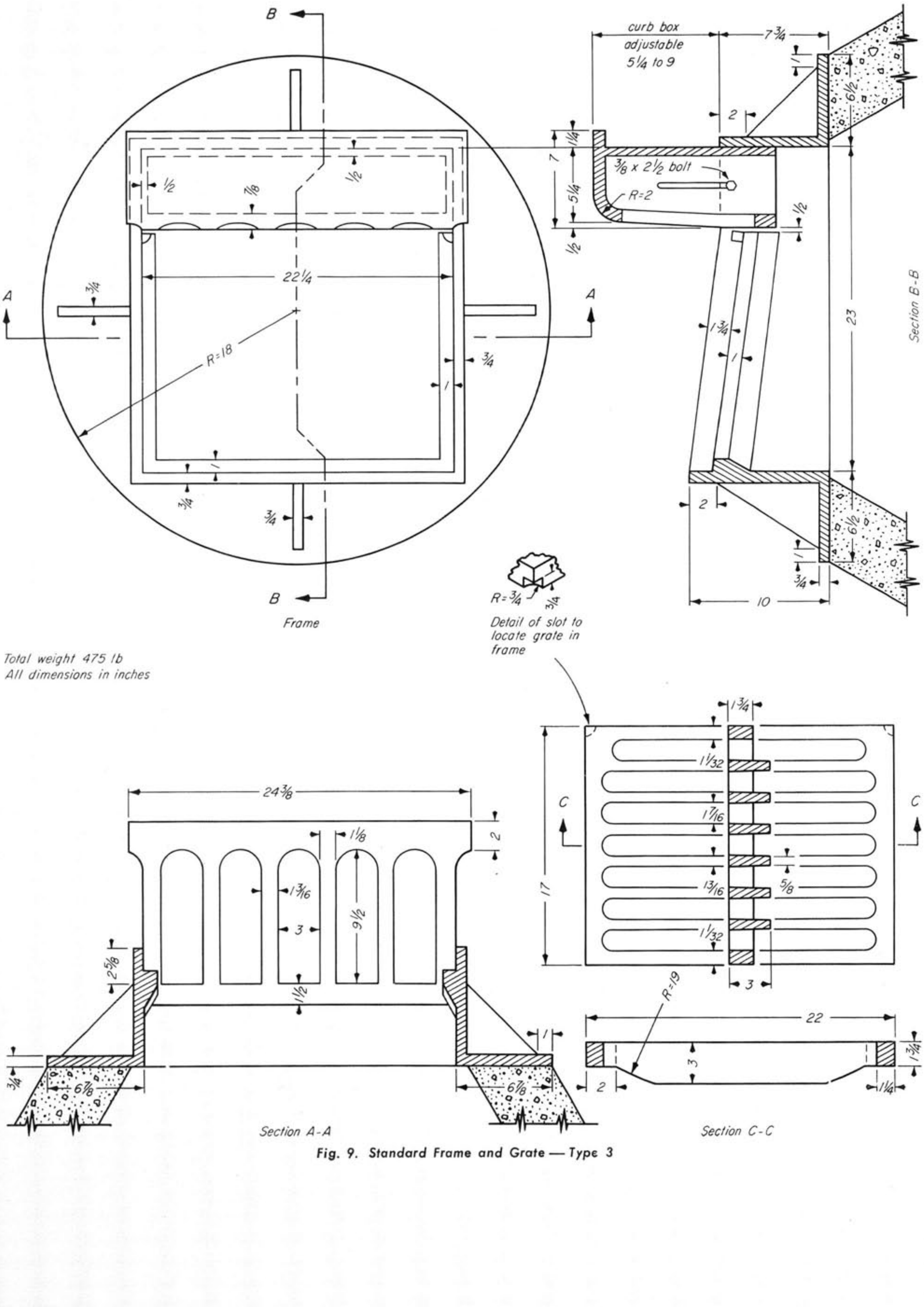


Fig. 9. Standard Frame and Grate — Type 3

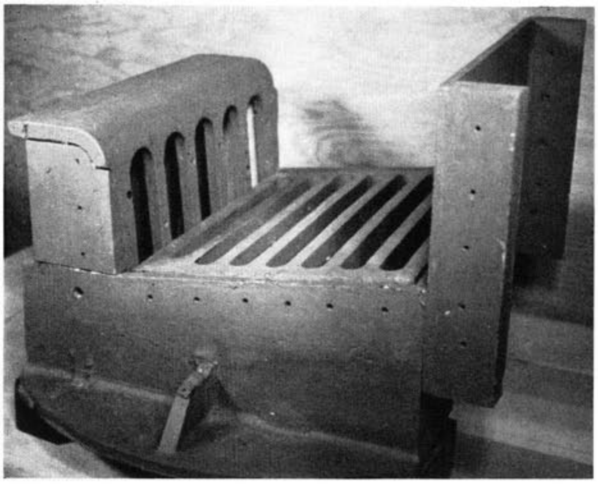


Fig. 10. Type 3 Inlet Frame with New Standard Inlet Grate

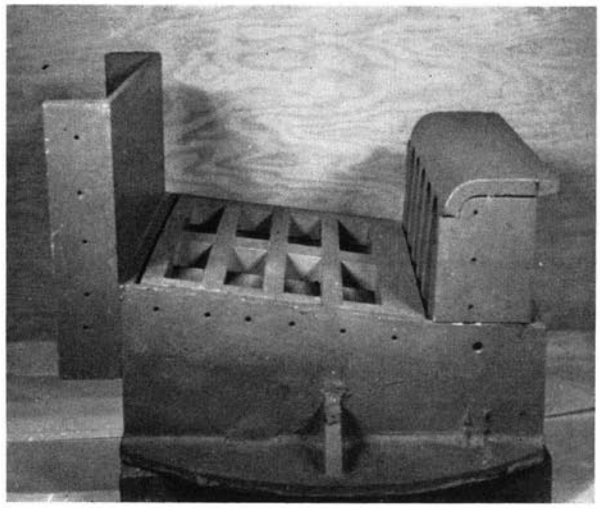


Fig. 11. Type 3 Inlet Frame with Old Standard Inlet Grate

grating, and when the length of nappe was just equal to the length of the inlet grate. In most cases, additional intermediate flows were required to emphasize or clarify certain portions of the inlet rating curve.

The model data pertinent to inlet efficiency was reduced to usable form while the tests were in progress. This procedure allowed the immediate realization of errors and of unusual interception characteristics. An interception efficiency curve, with intercepted flow as ordinate and total flow as abscissa, was plotted during the test operation to permit optimum selection of test flows and to avoid weak sections in the calibration data.

14. Type 3 Inlet Frame and Grate

The Illinois Division of Highways Type 3 Inlet Frame is designed to serve a barrier-type curb and gutter section. The curb face has a slight slope, and the gutter flag is 21 in. wide and has a 0.88 in. crossfall.

The standard inlet frame includes a curb opening inlet composed of five vertical openings. Each opening is 3 in. wide and about 7 in. high. The standard inlet grate, composed of six bars parallel to the curb face, is 22 in. long and 17 in. wide. The openings between the bars are approximately 1.5 in. wide. Detail dimensions of the inlet frame and grate are presented in Fig. 9. Both are constructed of cast iron and have a total weight of about 475 lbs.

It should be noted that the gutter is approximately 4 in. wider than the inlet grate on the pavement side of the roadway. The crossfall on the grate section is 2.25 in., about 1.33 in. greater than the corresponding gutter dimension. When the Type 3 inlet is installed in the field, the contractor is instructed to warp the gutter to the section of the inlet grate over a distance of about 10 ft. Thus, the interception characteristics of the grate are a function of the grate section, while the rate of water supply to the grate is a function of the original gutter capacity.

Laboratory determination of the interception characteristics of the Type 3 inlet was divided into two test series. The first series was devoted to determining the interception capacity resulting from simultaneous operation of the inlet grate and the curb opening structure. The second was performed with the curb opening blanked off. Thus determining the interception capacity of the inlet grate alone. For any given rate of flow, the difference between the first and second series data represents the interception capacity of the curb opening inlet.

After completion of the test work for each longitudinal slope, an old-style inlet grate was substituted for the parallel bar grate and the two test series were re-run, thus obtaining comparative data for the two grate styles with identical longitudinal gutter slopes.

The physical arrangement of the inlet grate and curb opening inlet are shown by Figs. 10 and 11. Both show the curb opening inlet open. Figure 12 pictures the new-style inlet grate with the curb opening inlet closed.

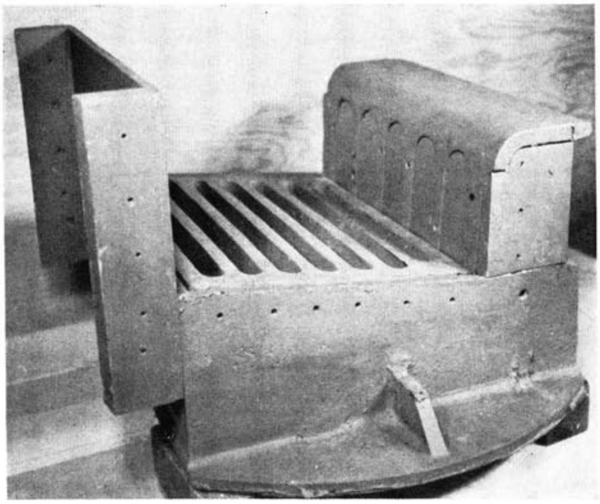


Fig. 12. Type 3 Inlet Frame, New Standard Inlet Grate, Curb-Opening Closed

Table 4

Approach Channel Data

Type 3 Inlet, New and Old Standard Grate, With and Without Curb Opening — 2% Slope

Run Number	Approach Channel Point Gage — ft No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	Flow Rate, cfs
	New Standard Grate — With Curb Opening							
1	0.143	0.130	0.124	0.118	0.118	0.119	0.111	0.200
2	0.210	0.211	0.201	0.191	0.190	0.187	0.174	0.646
3	0.269	0.266	0.253	0.242	0.241	0.238	0.217	1.098
4	0.325	0.332	0.317	0.295	0.279	0.280	0.257	1.616
5	0.401	0.370	0.377	0.352	0.333	0.330	0.302	2.12
6	0.448	0.403	0.407	0.404	0.378	0.374	0.337	2.60
7	0.500	0.448	0.453	0.445	0.414	0.426	0.374	3.06
8	0.554	0.513	0.491	0.467	0.446	0.464	0.408	3.59
	Old Standard Grate — With Curb Opening							
1	0.087	0.086	0.081	0.080	0.082	0.080	0.074	0.074
2	0.122	0.116	0.111	0.107	0.106	0.105	0.096	0.146
3	0.151	0.143	0.136	0.133	0.132	0.135	0.125	0.265
4	0.187	0.178	0.172	0.165	0.164	0.164	0.147	0.443
5	0.210	0.211	0.202	0.190	0.189	0.188	0.170	0.643
6	0.255	0.248	0.239	0.228	0.226	0.220	0.209	0.980
7	0.312	0.316	0.297	0.281	0.264	0.267	0.251	1.53
8	0.376	0.359	0.368	0.342	0.325	0.325	0.296	2.13
9	0.429	0.398	0.409	0.399	0.378	0.370	0.337	2.61
10	0.496	0.454	0.463	0.444	0.421	0.428	0.382	3.17
11	0.565	0.512	0.502	0.471	0.462	0.467	0.416	3.67
12	0.072	0.069	0.066	0.067	0.068	0.068	0.060	0.047
	New Standard Grate — Without Curb Opening							
1	0.071	0.068	0.066	0.067	0.067	0.067	0.053	0.044
2	0.102	0.098	0.096	0.092	0.093	0.092	0.082	0.106
3	0.140	0.130	0.123	0.117	0.117	0.118	0.112	0.199
4	0.159	0.151	0.151	0.145	0.143	0.142	0.133	0.319
5	0.187	0.177	0.171	0.165	0.165	0.163	0.151	0.440
6	0.210	0.212	0.202	0.192	0.189	0.188	0.177	0.544
7	0.237	0.228	0.226	0.215	0.212	0.212	0.197	0.854
8	0.272	0.269	0.260	0.242	0.242	0.241	0.226	1.12
9	0.330	0.327	0.317	0.293	0.277	0.284	0.266	1.62
10	0.402	0.375	0.382	0.366	0.340	0.345	0.319	2.23
11	0.445	0.395	0.415	0.402	0.382	0.374	0.346	2.61
12	0.517	0.462	0.461	0.449	0.426	0.442	0.397	3.24
13	0.575	0.502	0.493	0.483	0.460	0.469	0.420	3.74
	Old Standard Grate — Without Curb Opening							
1	0.032	0.032	0.032	0.032	0.032	0.032	0.045	0.009
2	0.055	0.054	0.054	0.052	0.055	0.055	0.045	0.026
3	0.066	0.064	0.062	0.061	0.063	0.062	0.053	0.038
4	0.080	0.077	0.074	0.075	0.075	0.075	0.065	0.063
5	0.087	0.085	0.081	0.080	0.082	0.080	0.070	0.074
6	0.142	0.130	0.124	0.117	0.117	0.117	0.111	0.198
7	0.159	0.150	0.149	0.145	0.145	0.143	0.129	0.316
8	0.194	0.186	0.180	0.170	0.170	0.172	0.156	0.491
9	0.240	0.240	0.225	0.215	0.213	0.210	0.193	0.862
10	0.298	0.300	0.285	0.264	0.257	0.260	0.247	1.38
11	0.363	0.353	0.354	0.324	0.307	0.308	0.286	1.94
12	0.414	0.396	0.405	0.390	0.370	0.369	0.339	2.51
13	0.486	0.446	0.449	0.436	0.419	0.418	0.380	3.09
14	0.544	0.506	0.492	0.483	0.450	0.459	0.416	3.65

15. Analysis of Experimental Data

A description of the method employed in reducing raw data to usable form is presented to aid in evaluating the significance of the relationships evolved. Because the data reduction process was similar for all inlets studied, only the Type 3 inlet grate data are discussed in detail. Data from the 2% longitudinal slope tests have been selected for this example.

The first step in the development of the calibration data was the selection of the most representative point to measure the depth in the approach channel. The location of this point is dictated by two conflicting criteria. The point of measurement must be as far downstream from the entrance as possible to minimize the effect of entrance turbulence and to allow the development of uniform flow. At the same time, the point of measurement must be far enough upstream from the test section to minimize the effect of drawdown at the inlet.

For each of the inlets tested, the location of the point of measurement was determined by the preparation of flow profiles for the individual approach channel.

Approach channel data for the Type 3 gutter on a 2% longitudinal slope are presented in Table 4 which summarizes 329 point gage readings. This includes work with the old and new standard grate and with the curb-opening inlet both open and closed. Each of the point gages was pre-set to indicate depth directly. The readings in Table 4 are not the result of a zero subtraction process. In addition to the approach channel depth measurements, the test rates of flow are presented in the last column of the table.

Based on the tabulated data depth versus flow rating curves were prepared for each of the seven approach channel point gages. The line best fitting the experimental points was drawn on each of the curves. This line was taken as the depth-discharge relation for the particular gage location. Figure 13 presents these curves for the Type 3 inlet.

Preparation of flow profiles was the next step toward the selection of the optimum point for depth measurement. For specific rates of flow, the corresponding channel depths were taken from the depth-discharge curves for the various point gages. These data were plotted with depth of flow as abscissa and gage station as ordinate. By connect-

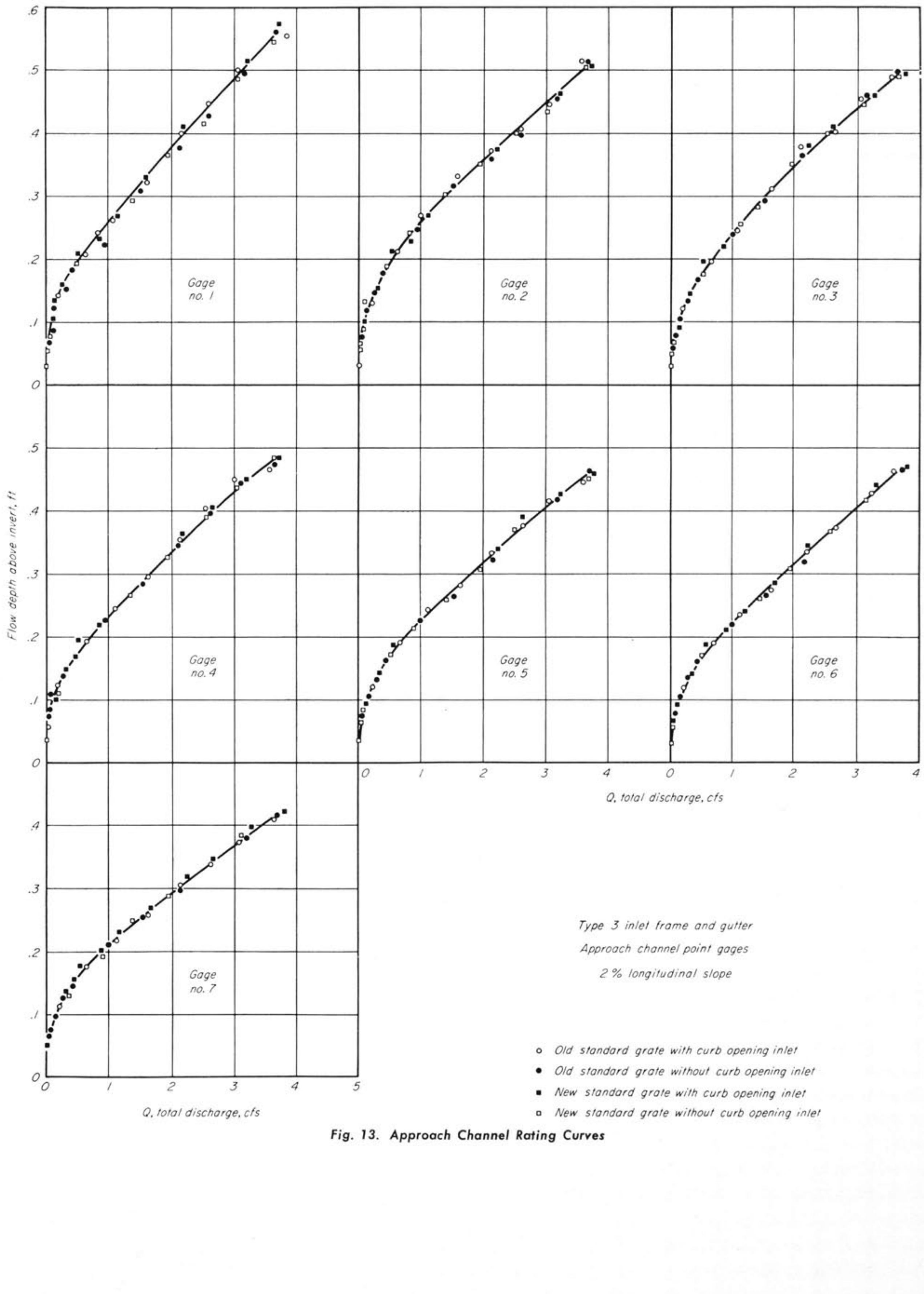


Fig. 13. Approach Channel Rating Curves

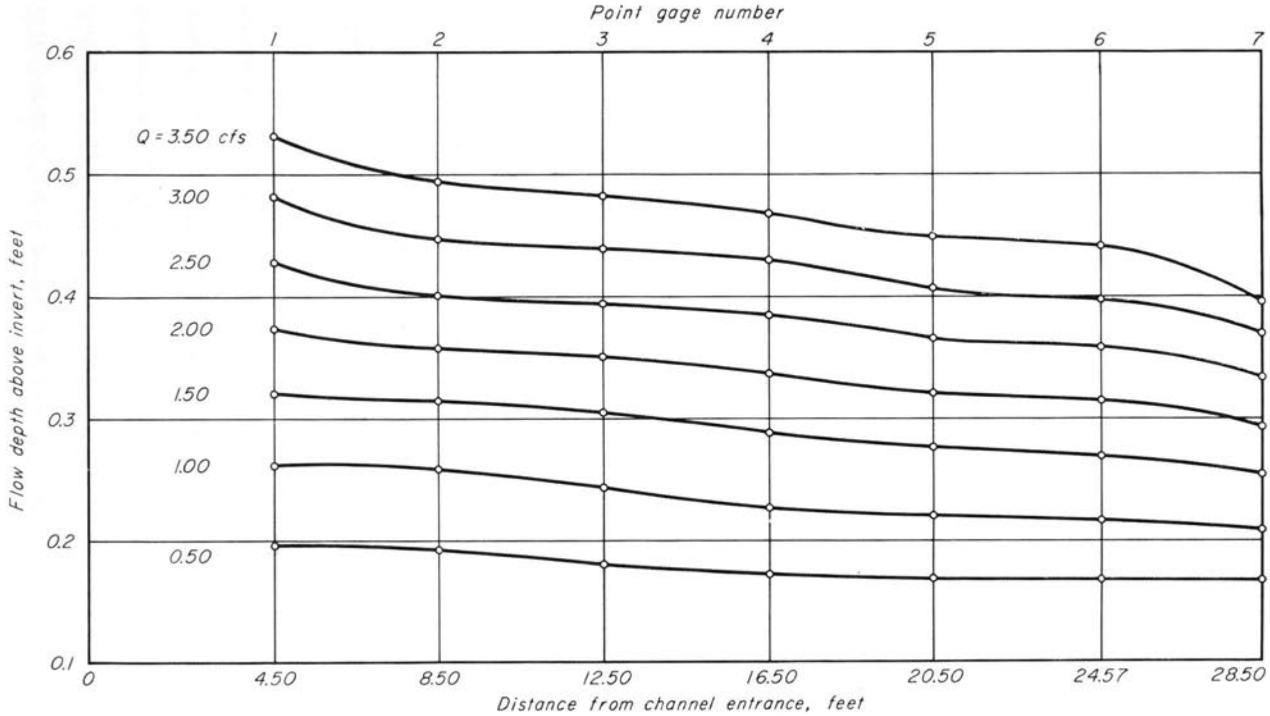


Fig. 14. Approach Channel Flow Profiles

ing the points for a given rate of flow, water surface profiles, given in Fig. 14, were produced.

Examination of the flow profiles shows that the depth of flow was continually greater than uniform depth at Gage 1. This characteristic indicated that the point of measurement must be located between Gages 5 and 7. The profile also indicates that between Gages 6 and 7 an appreciable increase in velocity was created by the proximity of the inlet opening.

Consideration of the water surface profile for the 2% longitudinal slope, and for the other six slopes that were tested, led to the adoption of the Gage 5 location for approach channel depth measurement. Similar studies of the Type 9, 10, and 11 approach channels indicated the same conclusion. Consequently, Gage 5 was utilized throughout the study to determine the approach channel depth.

The second step in developing calibration data was the determination of the two component flow rates as discussed in Section 12. The ratio of flow through the inlet, Q_I, to the total flow in the gutter, Q_G, is the interception efficiency of the inlet, which may be expressed as a percentage if multiplied by 100.

Efficiency curves are convenient for the design engineer, but are not of particular significance in the calibration of the inlet structures. In this report the calibration data are originally expressed with rate of flow in the gutter as the independent variable and intercepted flow as the dependent variable.

Again utilizing the 2% slope data as the example, Table 5 has been prepared to illustrate the manner in which the inlet calibration data were developed. These data have been taken directly from the laboratory calculation sheets, and it may be noted that all of the 2% slope data are presented. Some explanation of the flow rate determination may be desirable. Under the general headings, "Intercepted Flow" and "Carryover Flow," the first column is titled "Hook Gage Reading, ft." The figures in this column represent the actual gage reading. The second column of each general heading is the head, in feet of water, on the measuring weir. This figure is obtained by subtracting the gage zero from the reading of column one. Thus, considering Run 1 at the top of the table, a reading of 0.972 ft was obtained during the test work. From this figure the gage zero, 0.610 ft, was subtracted, and the head of 0.362 ft was obtained. Finally, the rating curve for the measuring weir indicated that when the head on the

Table 5

Flow Interception Data

Type 3 Inlet, New and Old Standard Grate, With and Without Curb Opening — 2% Slope

Run No.	Intercepted Flow			Carryover Flow			Total Flow Meter cfs	Channel Flow Q_G cfs	Interception Efficiency %
	Hook Gage Reading ft	Hook Gage Head ft	Rate of Flow cfs	Hook Gage Reading ft	Hook Gage Head ft	Rate of Flow cfs			
				New Standard Grate — With Curb Opening					
1	0.972	0.362	0.20	.....	.....	.....	....	0.20	100.0
2	1.181	0.571	0.64	1.036	0.085	0.006	....	0.646	99.1
3	1.323	0.713	1.08	1.085	0.134	0.018	....	1.098	98.4
4	1.434	0.824	1.57	1.146	0.195	0.046	....	1.616	97.3
5	1.527	0.917	2.02	1.219	0.268	0.10	2.01	2.12	95.3
6	1.590	0.980	2.40	1.305	0.354	0.20	2.56	2.60	92.3
7	1.642	1.032	2.70	1.406	0.455	0.36	3.08	3.06	88.2
8	1.697	1.087	3.01	1.504	0.553	0.58	3.59	3.59	83.8
				Old Standard Grate — With Curb Opening					
1	0.848	0.238	0.072	.....	.....	0.0015*	....	0.740	98.0
2	0.923	0.313	0.138	1.050	0.099	0.0085	....	0.146	94.5
3	1.004	0.394	0.248	1.084	0.133	0.0175	....	0.265	93.6
4	1.094	0.484	0.415	1.112	0.161	0.0285	....	0.443	93.8
5	1.169	0.559	0.600	1.143	0.192	0.043	....	0.643	93.3
6	1.257	0.647	0.870	1.231	0.280	0.11	....	0.98	88.8
7	1.352	0.742	1.21	1.381	0.430	0.32	....	1.53	79.2
8	1.431	0.821	1.56	1.501	0.550	0.57	....	2.13	73.2
9	1.479	0.869	1.80	1.587	0.636	0.81	2.51	2.61	69.0
10	1.537	0.927	2.10	1.661	0.710	1.07	3.14	3.17	66.3
11	1.570	0.960	2.27	1.749	0.798	1.40	3.66	3.67	61.9
12	0.807	0.197	0.047	.....	.....	.....	....	0.047	100.0
				New Standard Grate — Without Curb Opening					
1	0.803	0.193	0.044	.....	.....	.....	....	0.044	100.0
2	0.890	0.280	0.106	.....	.....	0.00035*	....	0.1064	99.7
3	0.970	0.360	0.197	.....	.....	0.00165*	....	0.1987	99.3
4	1.044	0.434	0.316	.....	.....	0.00347*	....	0.3195	99.0
5	1.102	0.494	0.435	1.032	0.081	0.0053	....	0.4403	98.7
6	1.181	0.571	0.535	1.050	0.099	0.0085	....	0.5435	98.5
7	1.249	0.639	0.840	1.072	0.121	0.014	....	0.854	98.3
8	1.328	0.718	1.10	1.105	0.154	0.025	....	1.125	97.8
9	1.430	0.820	1.55	1.177	0.226	0.065	....	1.615	96.0
10	1.531	0.921	2.06	1.287	0.336	0.17	....	2.23	92.3
11	1.573	0.963	2.32	1.366	0.415	0.29	2.60	2.61	88.8
12	1.635	1.025	2.68	1.497	0.546	0.56	3.24	3.24	82.7
13	1.678	1.068	2.95	1.579	0.628	0.79	3.68	3.74	78.9
				Old Standard Grate — Without Curb Opening					
1	0.706	0.096	0.009	.....	.....	.....	....	0.009	100.0
2	0.748	0.138	0.0205	.....	.....	0.0053*	....	0.0258	79.5
3	0.770	0.160	0.0288	1.055	0.104	0.0095	....	0.0383	75.2
4	0.827	0.217	0.0585	1.078	0.127	0.0157	....	0.0742	78.8
5	0.809	0.199	0.0478	1.070	0.119	0.0148	....	0.0626	76.2
6	1.022	0.412	0.275	1.139	0.188	0.041	....	0.316	87.0
7	0.948	0.338	0.167	1.118	0.167	0.031	....	0.198	84.3
8	1.101	0.491	0.434	1.165	0.214	0.057	....	0.491	88.4
9	1.217	0.607	0.740	1.243	0.292	0.122	....	0.862	85.8
10	1.322	0.712	1.08	1.372	0.421	0.30	....	1.38	78.3
11	1.386	0.776	1.34	1.512	0.561	0.60	....	1.94	69.0
12	1.440	0.830	1.60	1.618	0.667	0.91	2.44	2.51	63.8
13	1.494	0.884	1.88	1.698	0.747	1.21	3.09	3.09	60.8
14	1.524	0.914	2.01	1.800	0.849	1.64	3.59	3.65	55.0

* Determined by weight.

weir was 0.362 ft, the rate of flow over the weir was 0.20 cfs.

The next figure in the table, "Channel Flow, Q_G," is obtained by adding the carryover flow to the intercepted flow. Finally, "Interception Efficiency" is obtained by making use of the relationship:

$$\text{Interception Efficiency} = \frac{\text{Intercepted Flow} \times 100}{\text{Channel Flow}}$$

Calibration curves resulting from the tabular computations are given in Figs. 15 and 16. The curve for the 2% longitudinal slope data is in the lower left portion of each figure.

Figure 15 presents the new standard inlet grate calibration curves for each of the seven test slopes. The 0.125% slope and 0.25% slope data have been combined to form a single curve since there is no significant difference in the two sets of data. On each chart, the dashed line at an angle of 45° to the axis represents values of intercepted flow equal to total flow, or maximum possible interception.

Figure 15 shows no significant difference in the curves representing 0.125% to 1.0% longitudinal slopes when the flow in the gutter is 2.5 cfs or less. When the slope is greater than 1.0%, the difference between total interception and actual interception becomes much greater.

The series of curves in Fig. 15 indicates an important characteristic of parallel-bar inlet grates. At any point on the curve, the slope of the curve multiplied by 100 is the interception efficiency. It may be noted that each curve is a tangent section and a gradual concave curve. The tangent section represents total interception, and the concave curve represents a gradual loss of interception efficiency.

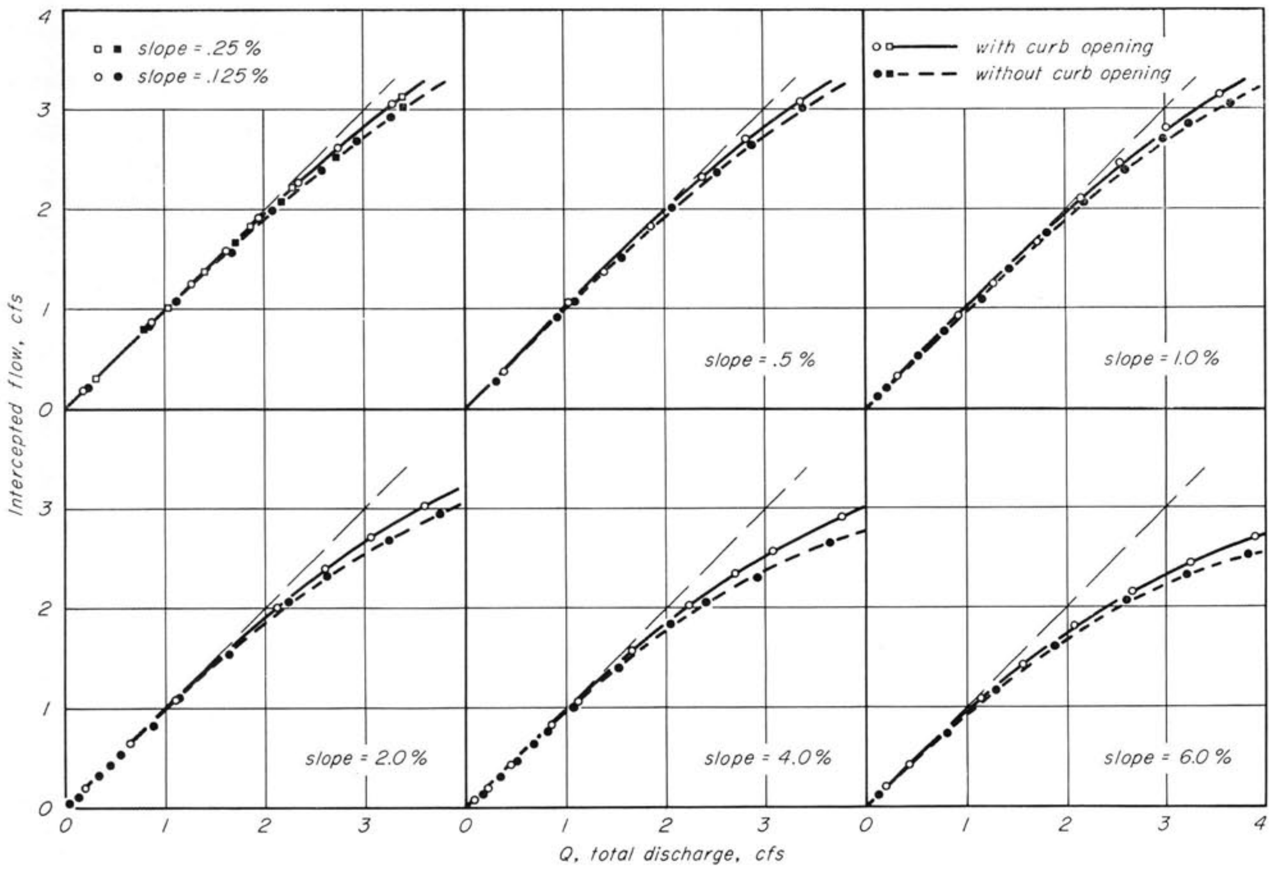


Fig. 15. Type 3 Inlet Calibration Curves — New Standard Grate

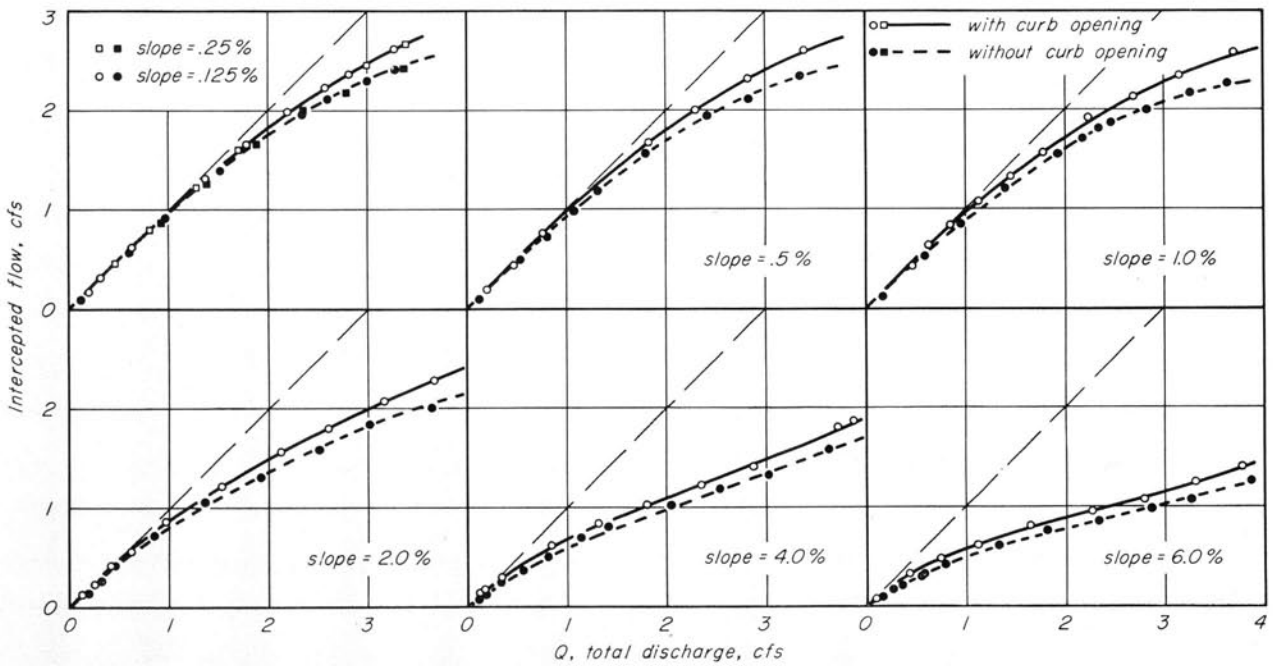


Fig. 16. Type 3 Inlet Calibration Curves — Old Standard Grate

This loss is caused by the gradual increase in gutter velocity. Since the inlet grate opening is of fixed length, *i.e.*, between any two longitudinal bars there is but one opening, the gradual increase in velocity of flow causes a gradual decrease in the slope of interception curve.

The curves of Fig. 15 show that the rate of flow intercepted by the curb opening is not primarily affected by the longitudinal slope of the gutter. The curb opening inlet tested in the laboratory intercepted about the same amount of total flow on both mild and steep slopes. For example, when the longitudinal slope was 0.125% and the gutter flow was 3.0 cfs, the flow through the curb opening was about 0.16 cfs. When the longitudinal slope was 6%, with the same total rate of flow, the curb opening interception was 0.12 cfs. The change in slope caused a decrease of 0.04 cfs, and the corresponding change in total interception was 1.30 cfs.

Inlet calibration curves for the old standard inlet grate, with and without the curb opening, are presented in Fig. 16. Again, the 0.125% slope data have been combined with the 0.25% data to form a single set of curves since there is no significant difference in the interception relationships. However, unlike the new standard data, there is a significant difference between the 0.25% and 0.50% slope-interception relationship. The difference in interception capacity must be attributed to the transverse bars that are included in the old-style design.

The transverse grate bars are also responsible for a change in general shape of the calibration curves. Figure 16 shows the curves are composed of two tangent sections and one concave curve. The initial tangent portions of the Fig. 16 curves represent total interception. Following this is a gradual curve that is concave downward, representing a gradual decrease in interception efficiency due to the gradual increase in flow velocity.

In the case of the parallel bar inlet grate, the concave portion of the curve continued to the maximum rate of flow tested in the laboratory. This action is not true of the "checkerboard" pattern inlet grate. Figure 16 indicates that the concave portion of the calibration curve is short, merging with a second tangent relationship at higher rates of flow.

Considering the curve for 2% longitudinal slope with the curb opening, it has been found that when the total discharge is greater than 1.5 cfs the experimental data fit the equation

$$Q_I = 0.50Q + 0.50 \qquad (15)$$

where Q_I is the intercepted flow, and Q is the flow in the approach channel, both measured in cfs.

On the same curve, when the rate of flow is less than 0.6 cfs, the intercepted flow is equal to the total flow. Thus, in the flow range 0.6 to 1.5 cfs, the interception curve is transitional between the two equational relationships. This type of equational relationship applies to all the curves in Fig. 16. Other studies have indicated that the functional equation describing inlet grate calibration curves may best be handled in exponential form.

The change in the shape of the interception curve is caused by the transverse bar of the inlet grate. The concave section of the curve is limited by the length of the first opening between the longitudinal bars. Figure 11 shows the two such openings in the old standard inlet grate. Information available at this time indicates that when the bulk of the flow reaches the gutter plane at the transverse bar, the concave portion of the curves describes the interception capacity. When the rate of flow is greater than this critical value, the interception pattern is disturbed and the inlet grate will function on a straight line basis.

Figure 16 indicates that in general the curb opening inlet receives about the same flow regardless of the approach channel slope. For a given rate of flow in the approach channel, the curb opening inlet intercepts more flow when used in conjunction with the old-style grate than it does in conjunction with the new-style grate. The turbulence created by the transverse bar increases the depth of flow over the top of the inlet grate, causing a higher head on the openings of the curb inlet, and more flow moves into the curb-opening structure.

Flow characteristics of the Type 3 grate with the curb inlet open are shown in Figs. 17 and 18. The rate of flow in Fig. 17 with the parallel bar inlet grate is 1.62 cfs and the interception efficiency is 97.3%. In Fig. 18 the flow is 1.53 cfs or about 8% less, and the interception efficiency is only 79.2%. The difference in efficiency is due entirely to the difference in the inlet grate patterns.

Figures 19 and 20 show conditions of flow when the curb inlet is closed. Figure 19 depicts a flow

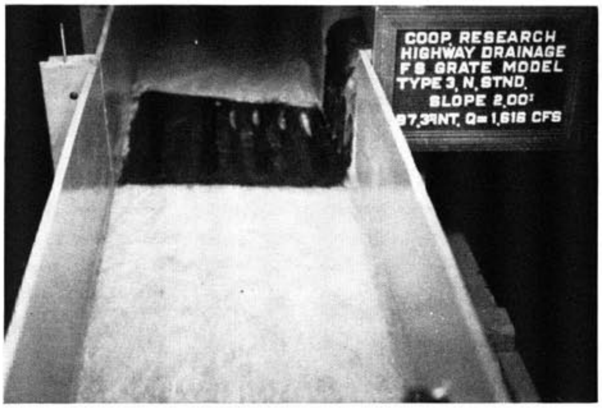


Fig. 17. Type 3 Inlet, New Standard Inlet Grate, Curb-Opening Open

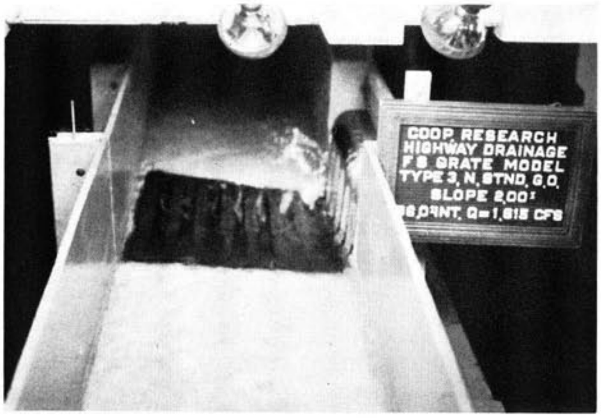


Fig. 19. Type 3 Inlet, New Standard Inlet Grate, Curb-Opening Closed

rate of 1.62 cfs and an interception efficiency of 96.0%. The flow rate in Fig. 20 is 1.38 cfs, and the interception efficiency is 78.3%. In this example, with about 17% less water presented to the old style inlet grate, the interception efficiency is much lower. In both cases the longitudinal slope is 2.0%.

Figures 17 and 19 form an interesting example. The rate of flow and the inlet grate are the same in both channels. The interception efficiency is 1.3% less when the curb-opening is closed. Careful examination of the pictures shows that when the curb-opening is open (Fig. 17), only a small amount of water flows along the grate bar that is against the curb inlet. When the curb-opening is closed (Fig. 19), a much larger portion of the total flow moves past the inlet on this bar. The splash at the downstream end of the first bar in Fig. 19 is an excellent example of this behavior.

16. Type 9 Inlet Frame and Grate

The Illinois Division of Highways Type 9 inlet grate is used in conjunction with a 36-in. "V"-type gutter. The gutter invert is at mid-width and is 3 in. below the edge of the adjacent pavement. The outside edge of the gutter is 6 in. above the invert, and two inches above the edge of the pavement. The gutter is not intended to flow full since this would cause water to encroach 10 ft onto the pavement. The design depth of flow in the gutter is normally about 4 in.

The Type 9 inlet is 24.5 in. wide with the invert at mid-width, and with the same cross slope as the gutter. The new standard inlet grate is composed of eight parallel bars, each 0.88 in. wide, and nine openings with a width of 1.5 in. The over-all length of the grate is 22.75 in. and the length of the openings between bars is about 20 in. Detail dimensions

Fig. 18. Type 3 Inlet, Old Standard Inlet Grate, Curb-Opening Open

Fig. 20. Type 3 Inlet, Old Standard Inlet Grate, Curb-Opening Closed

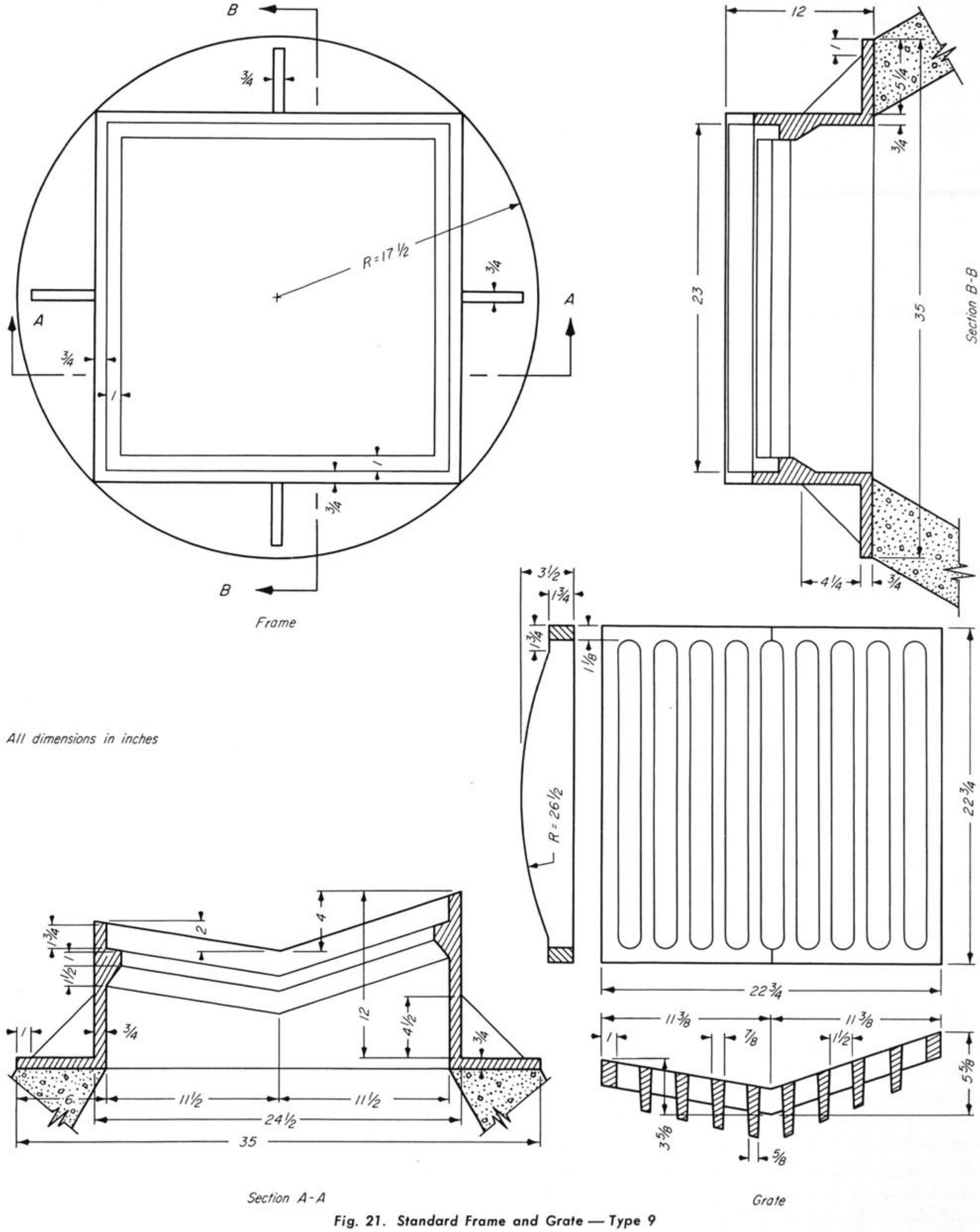


Fig. 21. Standard Frame and Grate — Type 9

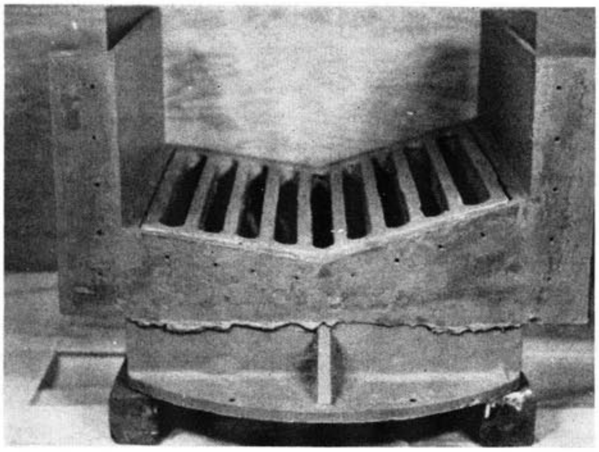


Fig. 22. Type 9 Inlet Frame with New Standard Inlet Grate

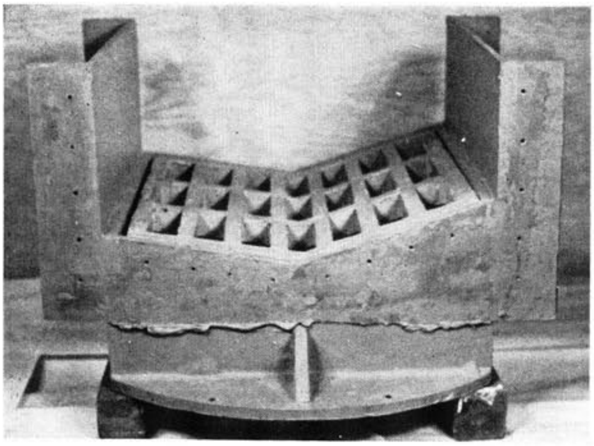


Fig. 23. Type 9 Inlet Frame with Old Standard Inlet Grate

of the 440 lb, cast iron inlet frame and grate are given in Fig. 21.

The interception capacity tests of the Type 9 inlet included both the old and new standard designs. Calibration of the two grates was performed in sequence so that both grates were tested with identical approach channel slopes.

The physical characteristics of the inlet grate test sections are shown in Figs. 22 and 23. The side boards were added to the gutter section to accommodate tests with flow depths greater than 4 in. Figure 23 pictures the old style inlet grate, which included two transverse grate bars and seven longitudinal bars. This pattern results in many

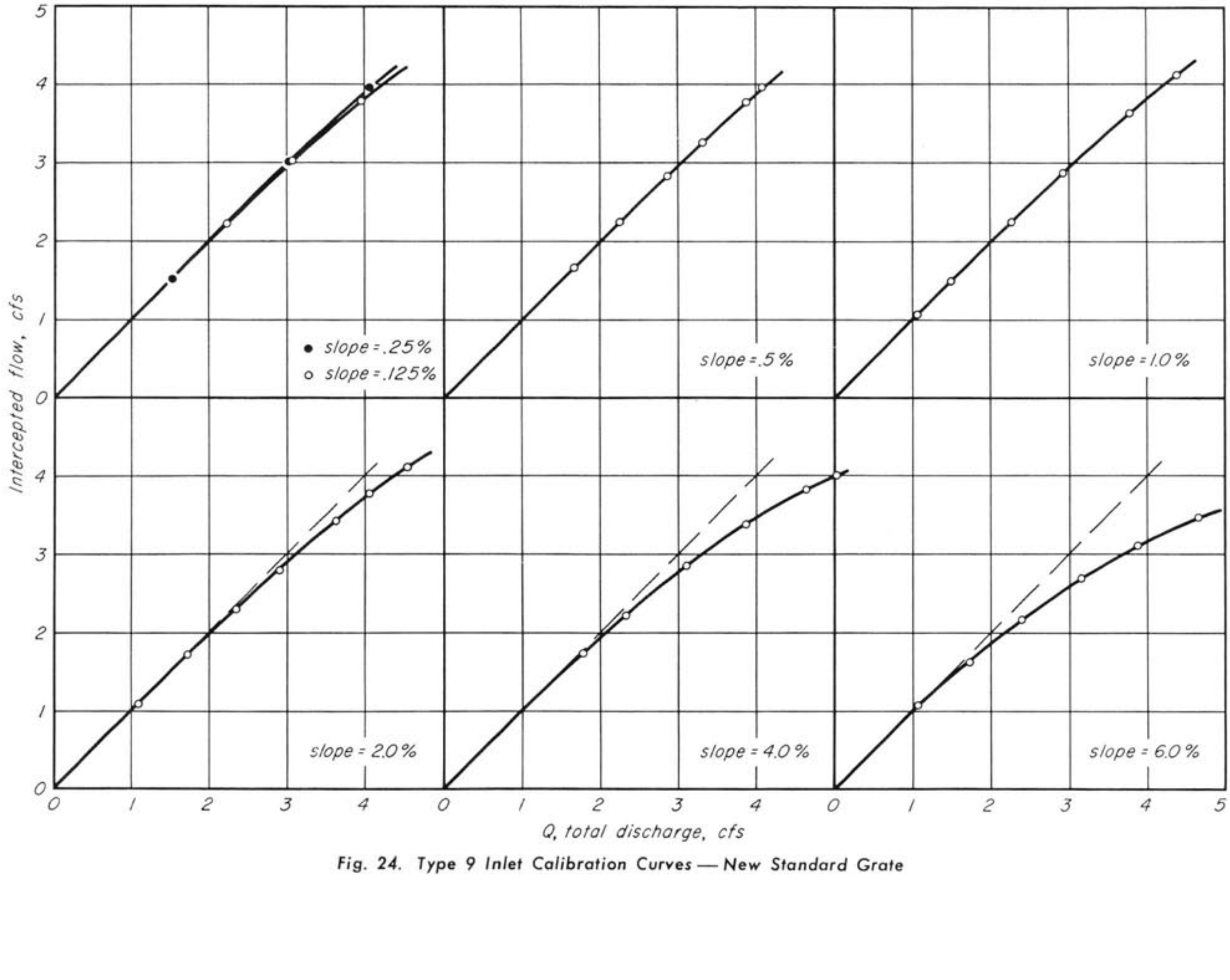


Fig. 24. Type 9 Inlet Calibration Curves — New Standard Grate

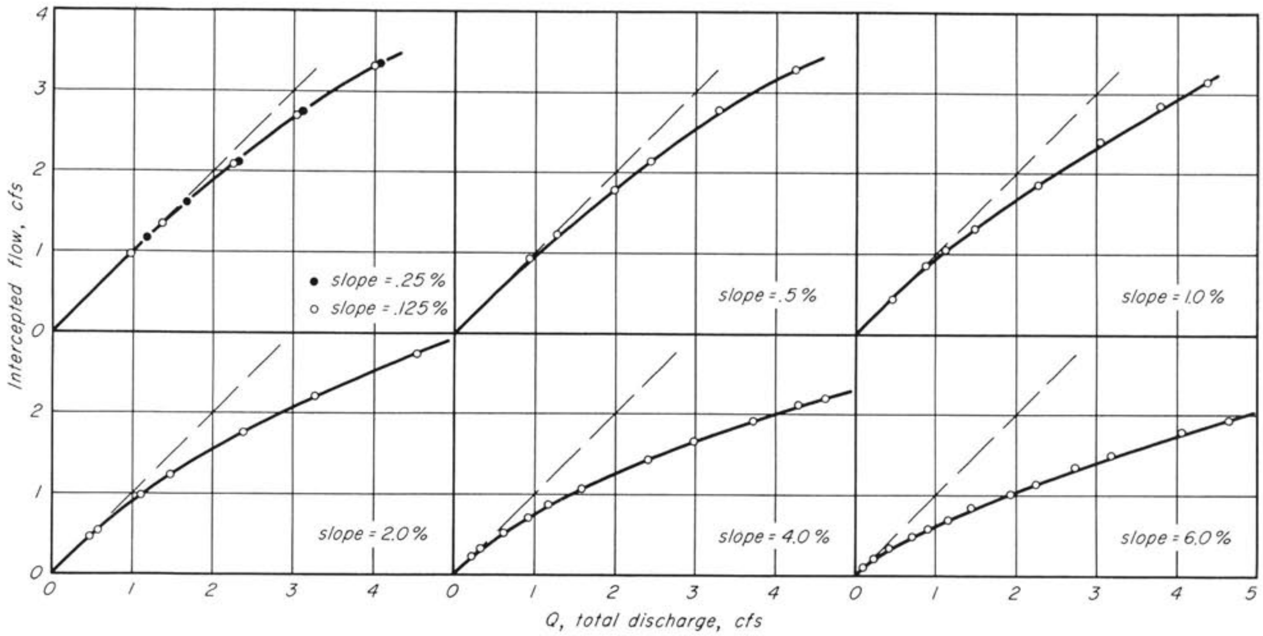


Fig. 25. Type 9 Inlet Calibration Curves — Old Standard Grate

small inlet grate openings, each about 2 in. wide and 6 in. long.

Calibration curves for the new standard Type 9 inlet grate are given in Fig. 24. The 0.125% slope curve is presented on the 0.25% slope chart, and the calibration curve for each slope is indicated. The dashed line on the charts indicates the line of complete interception. This line has been omitted on the 0.125, 0.25, 0.5, and 1.0% slope charts. The inlet grate intercepted nearly all of the approach channel flow when tested on slopes less than 2.0%.

The calibration curves for longitudinal slopes of 2.0, 4.0, and 6.0% exhibit the gradual concave curve typical of the parallel bar inlet grate.

Results of studies with the old standard grate are presented in Fig. 25. The calibration curves for the 0.125 and 0.25% slopes are coincident because of the transverse bars of the inlet grate. The bars obstruct the flow so much that the approach channel velocity is not a valid criterion for determining interception ability.

The interception curves for slopes greater than 0.5% indicate that a large portion of the gutter flow passes over the inlet. This characteristic is particularly important in "V"-type gutters because they are normally used in rural areas where high design flows and steep gutter slopes predominate.

Typical flow patterns for the Type 9 inlet are presented in Figs. 26 and 27. Examination of Fig. 26 shows how small carryover flows develop by water running over the top of the inlet grate bars when using the parallel-bar inlet grate. This

Fig. 26. Type 9 Inlet with New Standard Inlet Grate

Fig. 27. Type 9 Inlet with Old Standard Inlet Grate

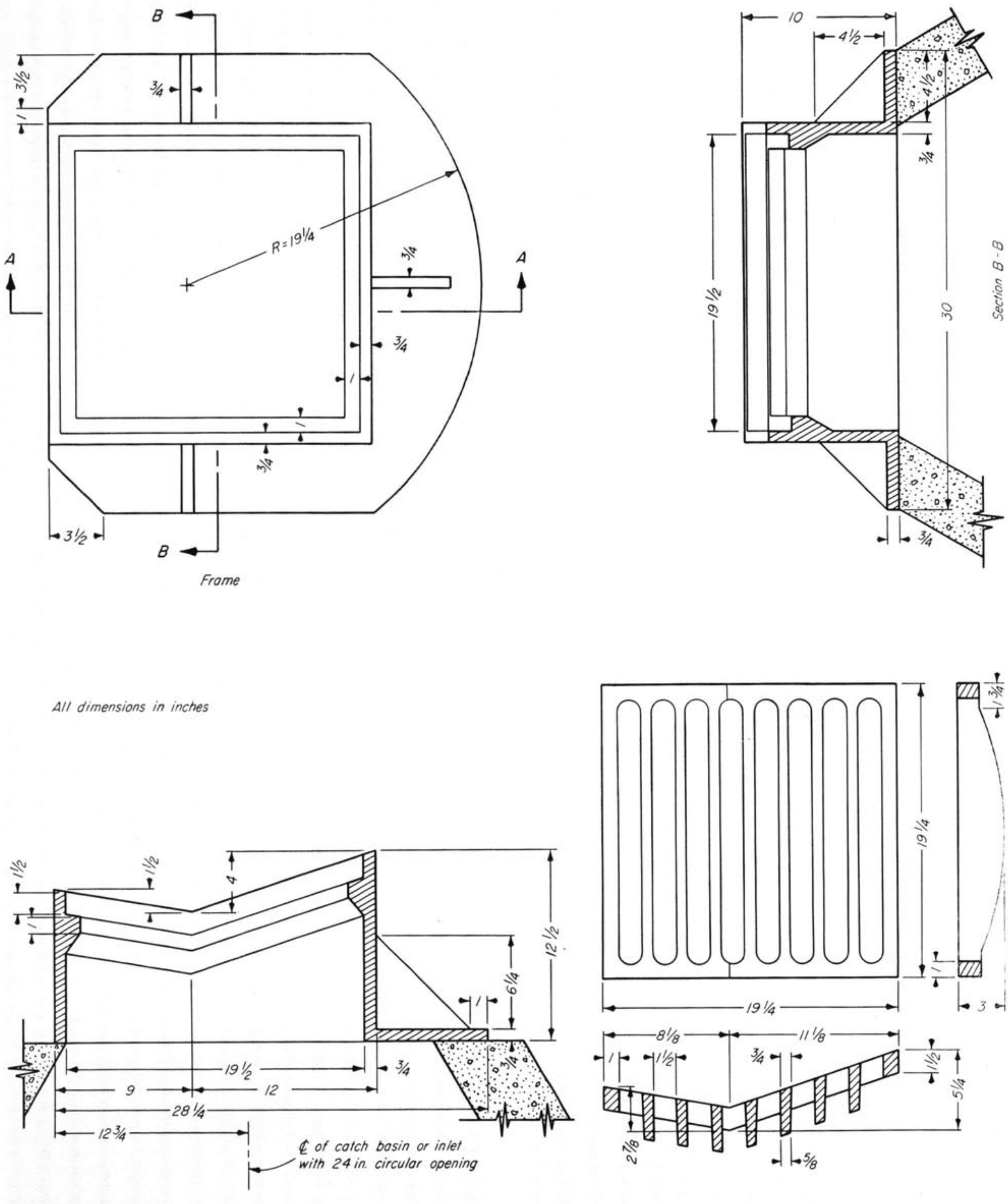


Fig. 28. Standard Frame and Grate — Type 10

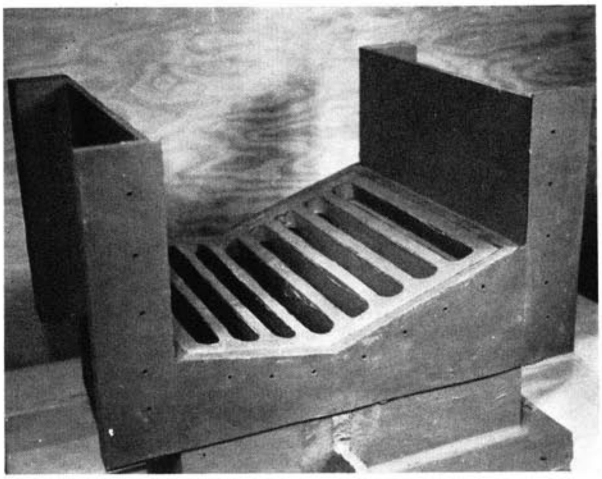


Fig. 29. Type 10 Inlet Frame with New Standard Inlet Grate

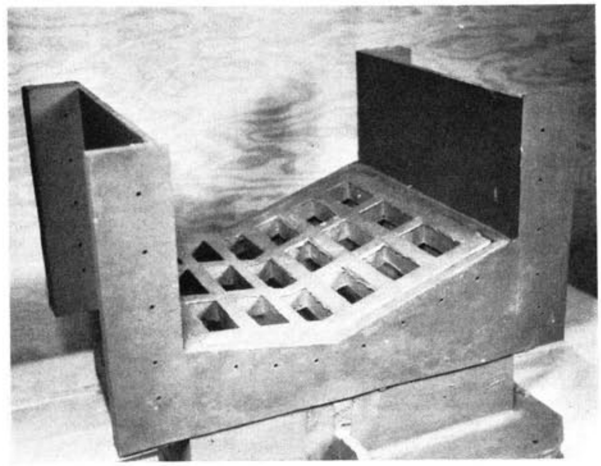


Fig. 30. Type 10 Inlet Frame with Old Standard Inlet Grate

action could be prevented with rounded bars, or by placing a notch at the downstream end of the bars. However, the carryover rate is so small it is not objectionable.

Figure 27 shows the flow pattern for the old-style inlet grate. The rate of flow is 2.27 cfs, nearly the same as in Fig. 26, and the longitudinal slope is identical in both figures. The interception efficiency in this test is only 82.8%, as compared to 99.5% with the parallel-bar inlet grate.

17. Type 10 Inlet Frame and Grate

The Illinois Division of Highways Type 10 inlet frame and grate is used with a 21-in. "V"-type gutter. This gutter has considerably less capacity than the 24-in. gutter, not only because of the decreased width, but primarily because of the smaller depth. The invert of the 21-in. gutter is 1.5 in. below the edge of pavement. The outside edge of the gutter is 4 in. above the invert, and 2.5 in. above the edge of the roadway. When the gutter flows full, the adjacent pavement section will be submerged from the gutter to the center of the roadway.

The new standard inlet grate is square in plan and measures 19.25 in. in both directions. The grate is composed of seven parallel bars each 0.75 in. wide, and eight 1.5 in. openings. The length of the openings between the bars is about 17 in. The old-style inlet grate is composed of five longitudinal bars and two transverse bars, with the individual openings approximately 2.0 by 4.75 in.

Detail dimensions of the Type 10 cast iron inlet frame and grate (combination weight, 360 lbs) are presented in Fig. 28. Laboratory studies of the Type 10 inlet capacity included both the new and old standard inlet grates. The calibration of the two grates was performed in sequence, to assure identical longitudinal slopes.

The arrangement of the test inlets is shown in Figs. 29 and 30. As with the Type 9 tests, sideboards were added to the inlet frame and to the gutter section to allow tests with flow depths greater than the gutter depth.

The interception curves resulting from the model investigation of the new standard Type 10 inlet are presented in Fig. 31. Data from the two milder slopes have been combined because the interception capacity is not affected by the change in channel slope. When the longitudinal slope is 0.5% or greater, it does change the interception characteristics. The capacity curves representing longitudinal slopes of 2.0% or more exhibit the concave shape that is characteristic of the parallel bar type of inlet. The dashed line indicates 100% interception.

Capacity curves resulting from studies with the old-style inlet grate are presented in Fig. 32. Comparison of the 6.0% and the 0.25% slope curves leads to an important understanding about the effect of transverse grate bars. When the rate of flow is small, both inlets intercept all of the channel flow. In this case, the physical factor that determines the interception capacity is a function of the open width at the upstream end of the inlet grate. It is proportional to the product of the width of the grate openings and the number of openings. This dimensional factor is the dominant intercep-

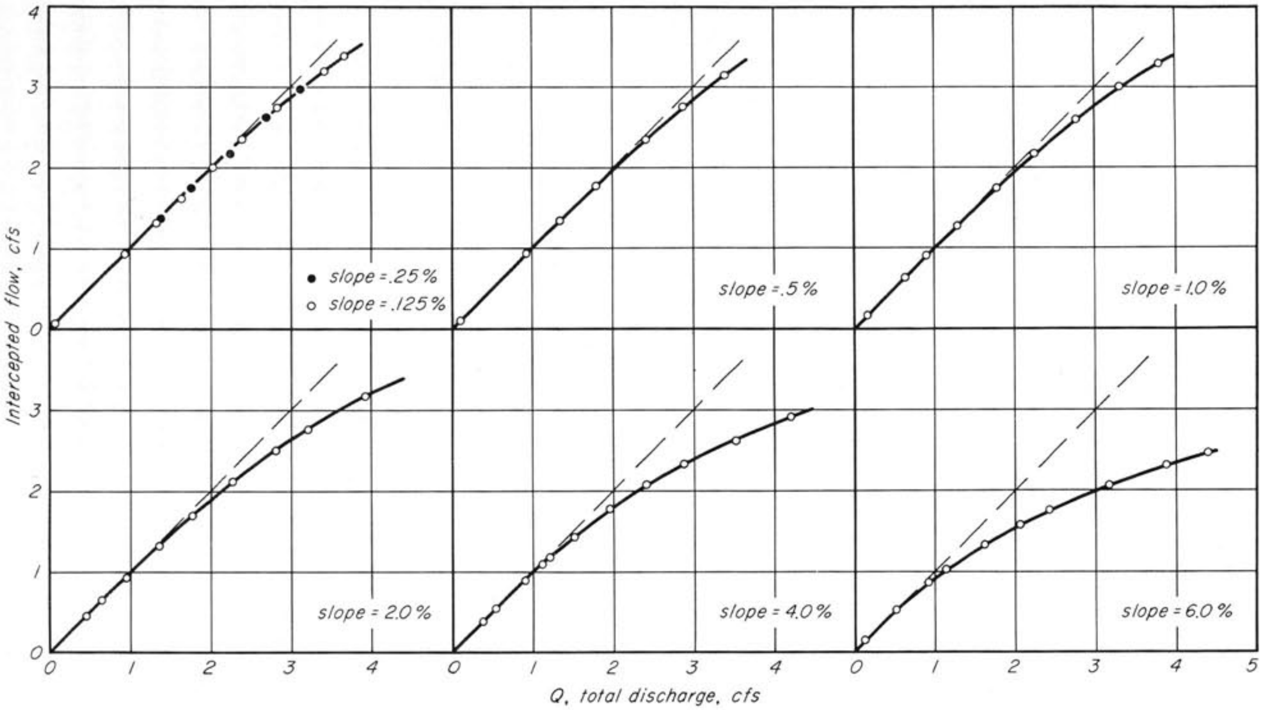


Fig. 31. Type 10 Inlet Calibration Curves — New Standard Grate

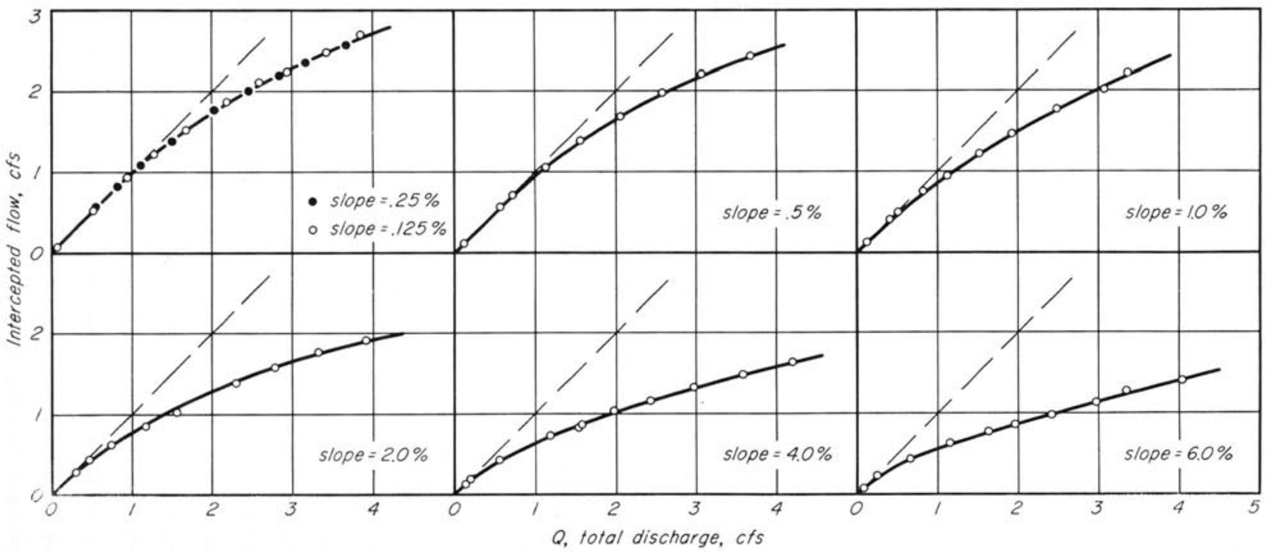


Fig. 32. Type 10 Inlet Calibration Curves — Old Standard Grate

tion criterion until the velocity of gutter flow becomes large.

This is proven by the 0.125% and 0.25% longitudinal slope curves. Even when the flow rate is relatively large, 2 cfs for example, most of the channel flow passes into the inlet because the longitudinal velocity of flow is small, giving the multiple openings in the grate time to act as orifices. For this condition, the transverse bars do not detract significantly from the interception capacity.

When the longitudinal slope causes a high velocity, the dimensional factor is no longer dominant. For example, the 6.0% slope curve indicates that less than 50% of a 2 cfs flow is intercepted by the

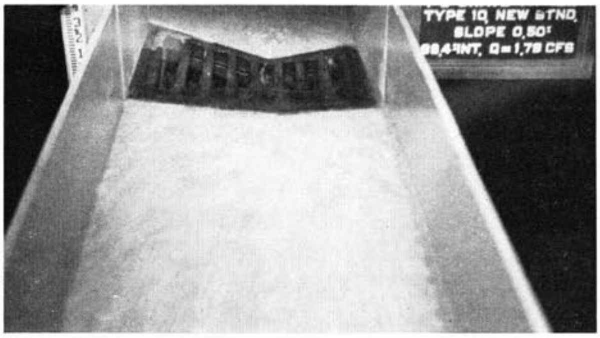


Fig. 33. Type 10 Inlet with New Standard Inlet Grate

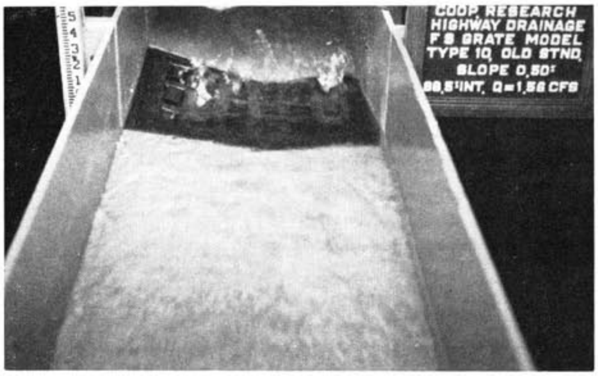


Fig. 34. Type 10 Inlet with Old Standard Inlet Grate

inlet grate. The dominant factor in this case is the length of inlet grate opening. When the length of opening is small and the channel velocity is high, the gutter flow does not have enough time to fall through the grate openings. Flow patterns of the Type 10 inlet on 0.5% longitudinal slope are shown in Figs. 33 and 34.

18. Type 11 Inlet Frame and Grate

The Illinois Division of Highways Type 11 inlet frame is designed to serve a barrier-type curb and gutter section. The curb face has a batter of 0.5 in. and the width of gutter is slightly over 12 in. The gutter crossfall is 1.0 in.

The standard inlet frame includes a curb inlet box with five openings, each about 4.5 in. wide and 7 in. high. The curb box is adjustable to serve curb heights of 4.5 to 9 in. Therefore, the setting of the box determines the height of curb openings. The new standard inlet grate, composed of four bars, each 0.88 in. wide, and five 1.25 in. openings, is 28.75 in. long and 11.63 in. wide. Detail dimensions of the inlet grate are given in Fig. 35. Both the inlet frame and grate are constructed of cast iron, and have a combined weight of 500 lbs.

Experimental evaluation of the interception characteristics for the Type 11 inlet was divided into two separate test series. The first series was devoted to the determination of the interception capacity that resulted from simultaneous operation of the inlet grate and the curb opening. The second test series was performed with the curb opening blanked off. From this series, the interception of the inlet grate alone was determined. For any given rate of flow, the difference between the first and second series data represents the interception capacity of the curb opening inlet. The interception capacity of both the new and old standard inlet grate was determined during each test series thus assuring that comparative data were obtained.

The arrangement of the Type 11 inlet frame, grate, and curb opening is shown by Figs. 36 and 37. Closure of the curb opening inlet was accomplished with a device similar to the one in Fig. 12.

Calibration curves for the Type 11 inlet with the new standard inlet grate are given in Fig. 38. The curves pertain to operation both with and without the curb opening inlet structure.

The curves indicate that, regardless of the test slope, the grate intercepts nearly all of the flow presented to the inlet when the gutter flow rate is less than about 2 cfs. A comparison of Figs. 38 and 15 shows that, for any given flow, the Type 11 inlet grate has a greater interception ability than the corresponding Type 3 inlet grate despite the fact that the Type 3 grate is more than 45% wider. The difference in capacity is primarily due to the greater length of the Type 11 inlet grate. When the flow rate is high and the gutter slope steep, the length of the parallel grating is the prime dimensional factor.

Figure 38 also shows that the curb opening inlet is of little value when the inlet grate is free of debris and obstructions. The Type 3 inlet tests yielded the same conclusion.

Interception capacity curves for the Type 11 inlet with the old-style inlet grate are shown in Fig. 39. It is noted that the curb opening inlet receives considerably more flow when the inlet grate contains transverse bars. This is particularly true when the approach channel is on a mild longitudinal slope.

Typical flow patterns on the Type 11 inlet are shown in Figs. 40 and 41. Figure 41 is especially interesting because it indicates the harmful effect

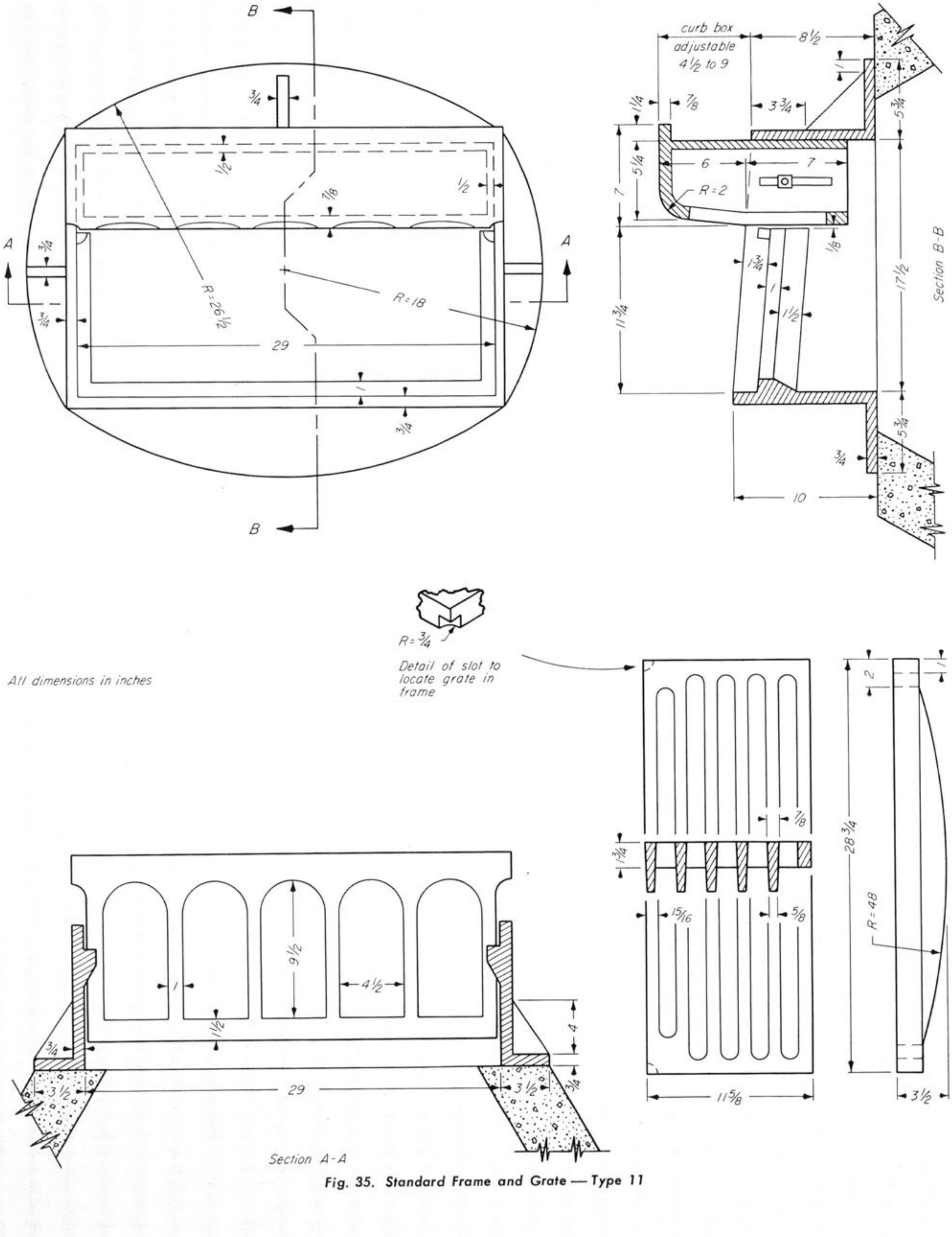


Fig. 35. Standard Frame and Grate — Type 11

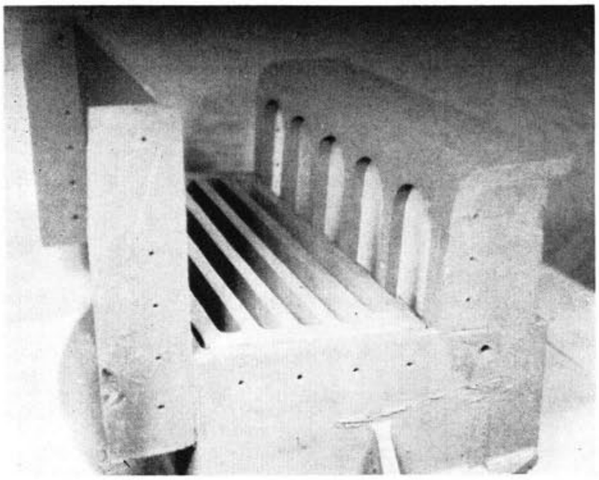


Fig. 36. Type 11 Inlet with New Standard Inlet Grate

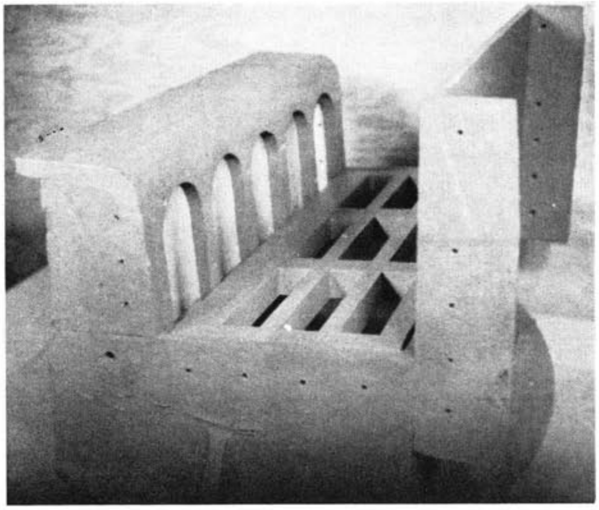


Fig. 37. Type 11 Inlet with Old Standard Inlet Grate

of the transverse bar in the inlet grate. It also shows that virtually no water is moving into the upstream opening of the curb inlet structure.

19. Interception Efficiency Curves

This section is intended to present the previously-discussed laboratory data in a somewhat different form. In certain cases, a better design picture of inlet operation may be obtained if the interception ability of the inlet grate is presented as a function of total channel flow. Usually, the preferred form of the function is as interception efficiency.

The interception efficiency of an inlet is defined as the ratio of intercepted flow to total gutter flow and is usually expressed as a percentage. The last column of Table 5 indicates the interception efficiency for the Type 3 inlet data. For example, the table shows that during Test Run 6, using the new standard inlet grate with the curb opening in operation, the total channel flow was 2.60 cfs and the

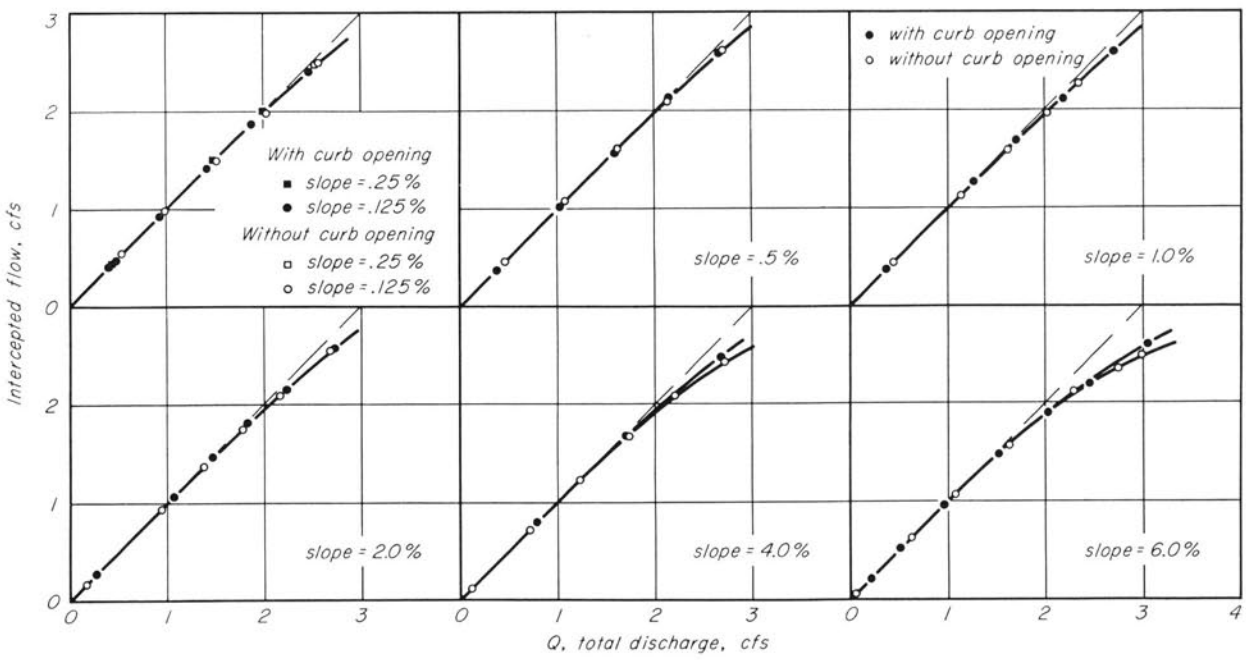


Fig. 38. Type 11 Inlet Calibration Curves — New Standard Grate

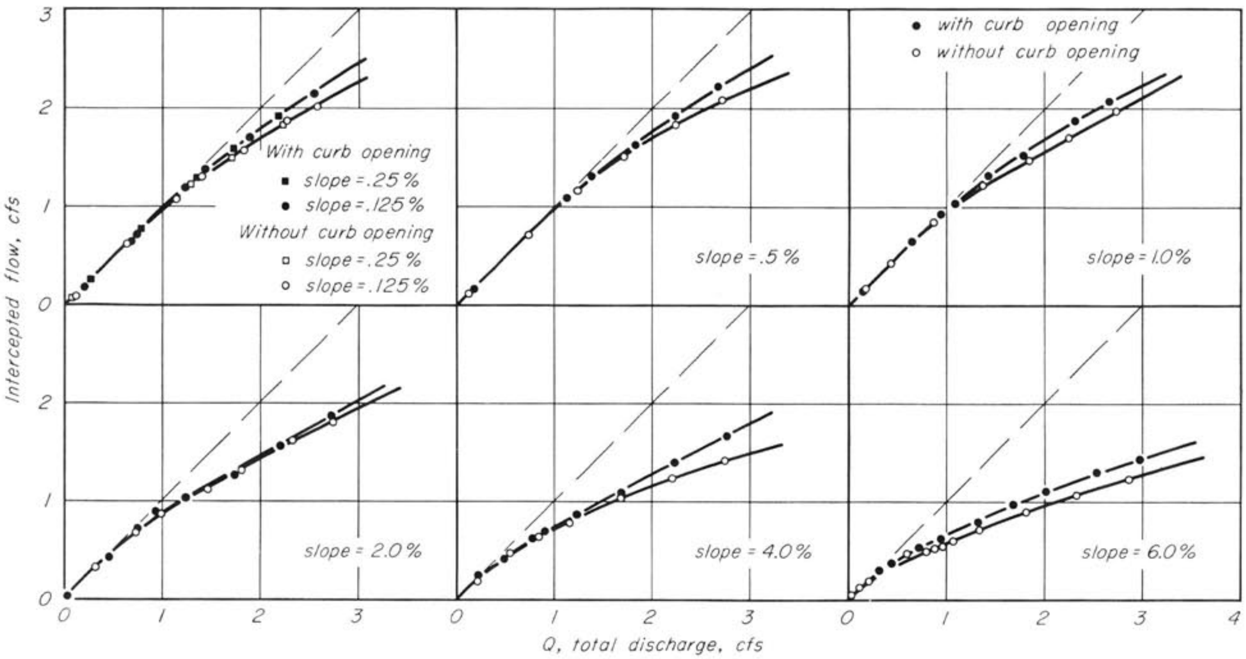


Fig. 39. Type 11 Inlet Calibration Curves — Old Standard Grate

intercepted flow was 2.40 cfs. The interception efficiency was

$$\frac{2.40 \times 100}{2.60} = 92.3\%.$$

This efficiency includes both the inlet grate and the curb opening inlet.

Reference to the portion of Table 5 that presents data for tests with the new standard grate, without the curb opening, allows the following calculation using Test Run 11 data.

$$\frac{2.32 \times 100}{2.61} = 88.8\%$$

This efficiency does not include the curb opening inlet.

Taking the difference in the two percentages shows that the interception efficiency of the curb opening alone is about 3.5%. Although for this example it was assumed that the approach channel flow rates were identical, they actually differed by about 0.38%.

Exact determination of the curb opening effi-

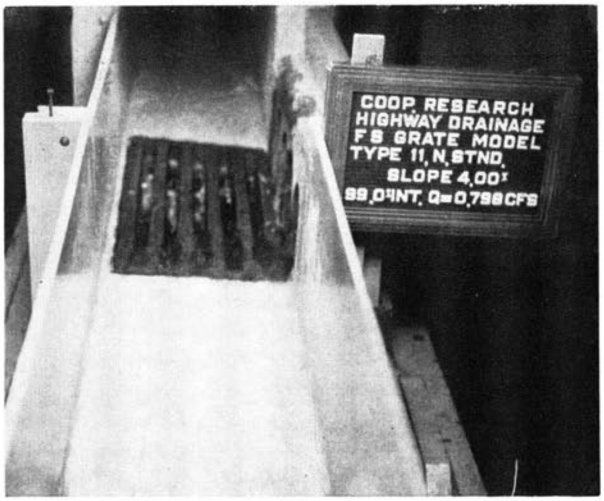


Fig. 40. Type 11 Inlet with New Standard Inlet Grate

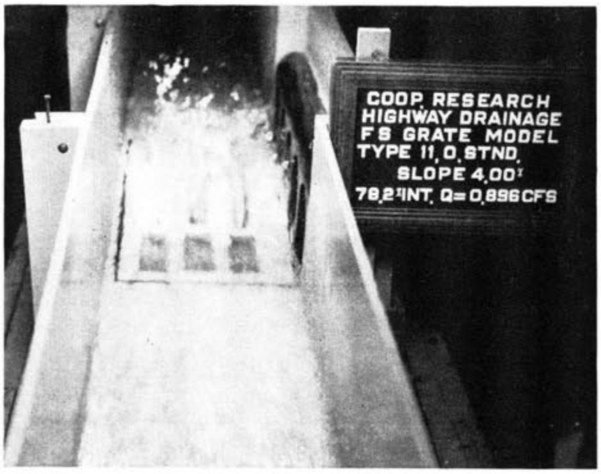


Fig. 41. Type 11 Inlet with Old Standard Inlet Grate

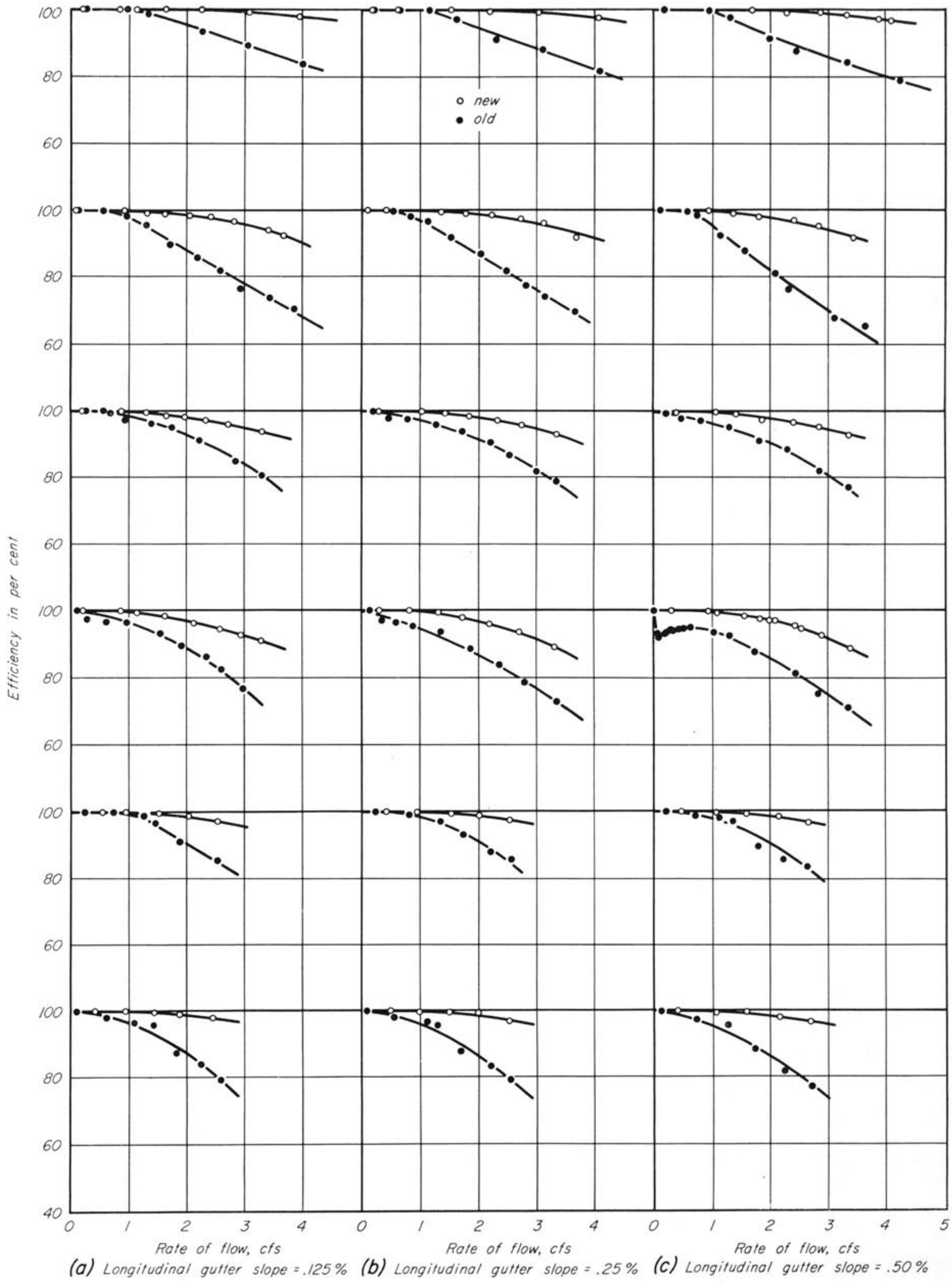


Fig. 42. Interception Efficiency Curves — Longitudinal Gutter Slope = .125%, .25%, .50%

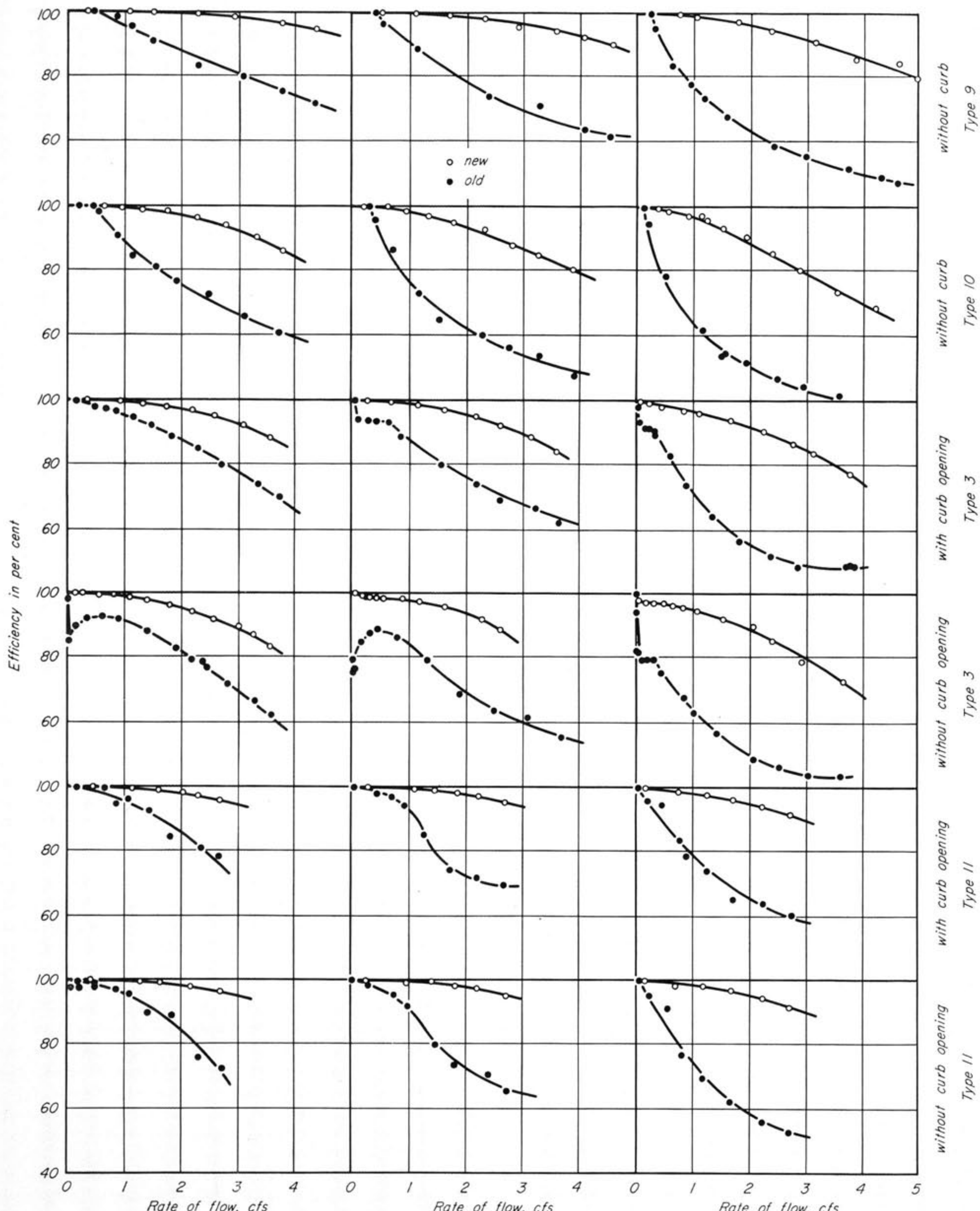


Fig. 43. Interception Efficiency Curves — Longitudinal Gutter Slope = 1.0%, 2.0%, 4.0%

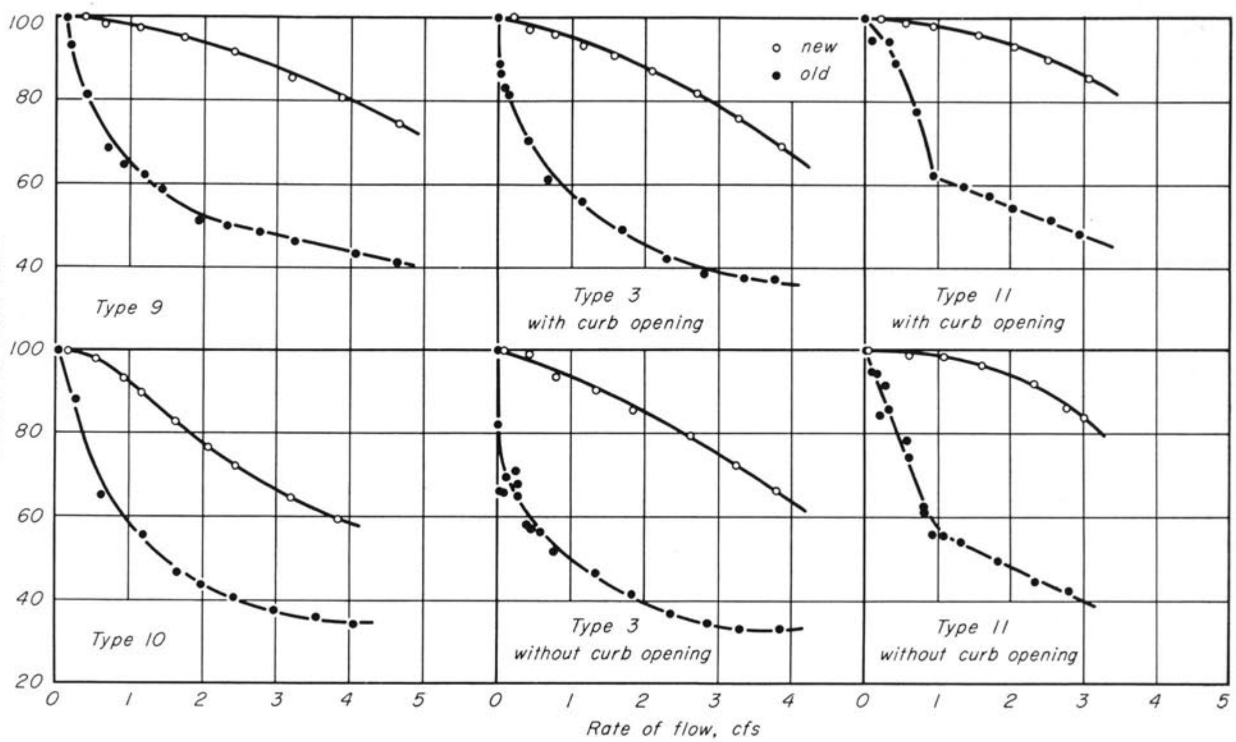


Fig. 44. Interception Efficiency Curves — Longitudinal Gutter Slope = 6.0%

ciency should be made by using the inlet efficiency rating curves, rather than by assuming equivalent flows in the approach channel.

The interception efficiency curves for the four inlets tested in the laboratory are presented in Figs. 42 to 44. The curves are grouped according to longitudinal channel slope rather than type of inlet. This grouping allows easy comparison of the old and new standard inlet grates. Two charts are given for the Type 3 and Type 11 inlets. The first pertains to interception efficiency with the curb opening open, and the second to the curb opening closed condition.

In addition to providing a direct means of comparing the old and new-style inlet grates, certain efficiency curves illustrate an interesting curb opening inlet characteristic.

The 0.50% slope curve, Fig. 42 indicates that the old style Type 3 inlet, without curb opening, exhibits an unusual low flow characteristic. The efficiency curve drops very sharply from 100% to approximately 92% efficiency. Examination of the corresponding curve for the same grate with curb opening inlet does not show this sharp decrease in efficiency. Moreover, Fig. 42 shows that the curve does not drop when the slope is less than 0.50%. Figures 43 and 44 indicate that the curve does drop when the slope is greater than 0.5%.

The efficiency curve drop indicates a relatively large carryover flow. Figure 11 reveals the reason for the carryover flow. In the Type 3 inlet, the longitudinal bar nearest the curb face is unusually wide. The other longitudinal bars are approximately 1.25 in. wide, but the curb bar is 2.50 in. wide. When the rate of flow is small and the velocity of flow is high, most of the gutter flow is concentrated at the curb face. When the curb opening is closed, much of this flow moves over the inlet opening on the curb bar. When the curb opening is open, the flow moves into the curb inlet because of lack of restraint at the individual openings. The same type of action occurred during the tests of the old-style Type 11 inlet. However, the crossfall in the Type 11 gutter is not sufficient to concentrate the flow and the increased carryover is not apparent in the interception efficiency curves.

V. THE DEVELOPMENT OF DESIGN CRITERIA

The laboratory interception capacity curves for any inlet, though interesting, are not of immediate practical value. Before the data can be applied by the designer, it is necessary to develop the correlations that exist between the results of the experimental program and the design factors with which the drainage engineer must work.

The development of a satisfactory street drainage program depends upon understanding the conditions of flow on the street surface, as well as the interception efficiencies of the gutter inlet grates.

The prime requisite for efficient storm water interception, regardless of inlet grate design, is the concentration of flow in the gutter area. No matter how advanced the design of the inlet grate may be, if the storm water is not presented to the inlet, it will not be intercepted.

The total rate of storm water flow on a street or highway may be considered in two parts: the flow in the gutter itself, and the flow on the pavement adjacent to the gutter. Contrary to popular belief, the two component flow rates do not freely mingle and mix as they move down the roadway surface, nor do the two components move with the same velocity. Due to the greater depth, the velocity of the gutter flow is considerably higher than that of the pavement flow. An example of this flow pattern is presented in Fig. 45.

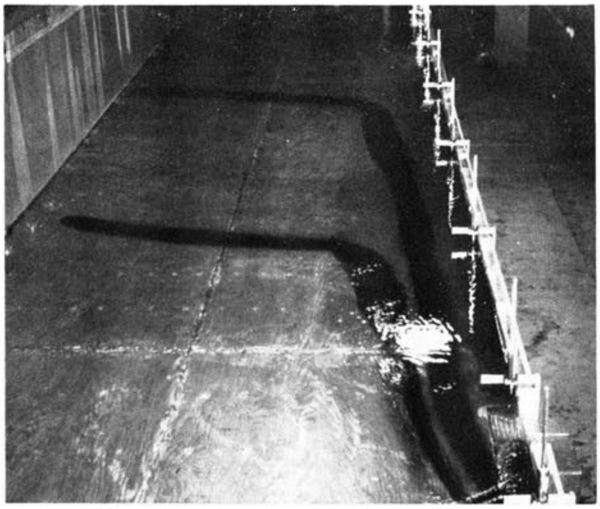


Fig. 45. Flow in Gutter and Pavement Section

The separation of storm water flow into two components is of considerable importance to the drainage system designer. By using this procedure, he can calculate the over-all interception efficiency of an inlet for any given flow rate. For example, assume that a flow of 2.50 cfs is moving in the combined gutter and pavement cross section. Assume further that 20% of the flow is on the street surface and that the remaining 80% of flow is in the gutter section. If experimental studies show that at the particular depth of flow, the inlet grate will intercept 90% of the flow in the gutter prism, the following calculation is possible:

Total Interception Efficiency $= 0.90 \times 0.80 \times 100 = 72\%$

Expressed in terms of the flow rate, the total interception is:

Total Interception $= 2.50 \times .90 \times .80 = 1.80$ cfs

Since the total flow rate was 2.50 cfs, and 1.80 cfs was intercepted by the inlet, the flow in the gutter downstream from the inlet must be 0.70 cfs. Initially, this flow will be on the pavement but, after passing the inlet, it will move rapidly into the gutter prism. This calculation assumes that the amount of storm water entering the inlet from the pavement is not significant. In most design cases this is true.

20. Gutter Flow Rating Curves

The rate of flow in a particular gutter for any depth, slope, and surface roughness may be determined by using the Manning equation. Rating curves for design use are composed of a series of such relationships plotted with depth of flow as ordinate and rate of flow as abscissa. Usually a series of such curves is used in design procedures, with each curve of the series representing a different longitudinal gutter slope.

To evaluate the individual factors that influence

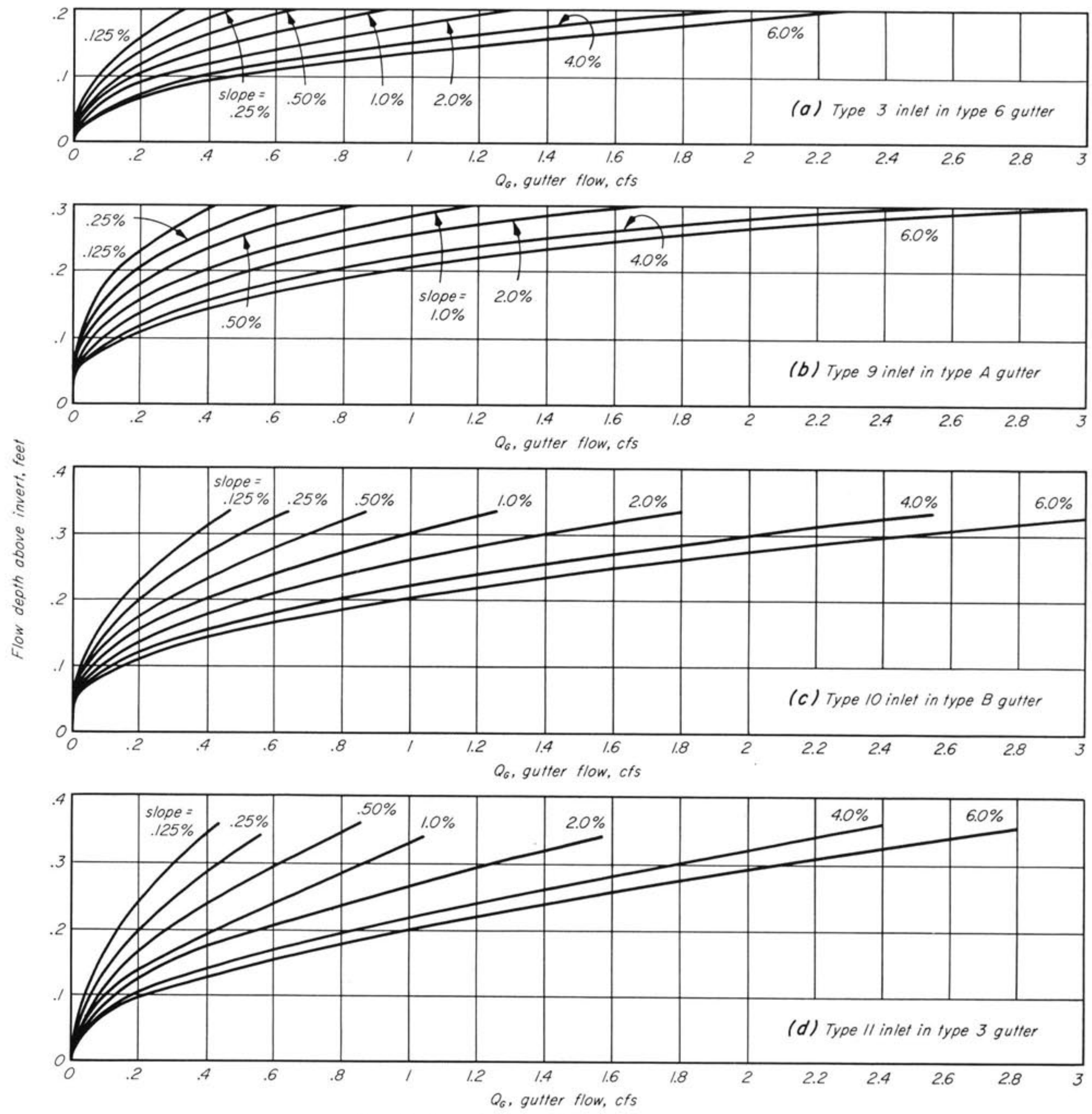


Fig. 46. Type 6, A, B and 3 Gutter Rating Curves

Table 6

Theoretical Rating Data — Type 6 Gutter

Manning Equation — Various Longitudinal Slopes

Depth ft	Area sq ft	Wetted Perimeter ft	$\frac{1.486A^{5/3}}{np^{2/3}}$	Rate of Flow for Indicated Slope 0.125% cfs	0.250% cfs	0.50% cfs	1.0% cfs	2.0% cfs	4.0% cfs	6.0% cfs
0.05	0.042	1.19	0.45	0.016	0.022	0.032	0.045	0.063	0.089	0.109
0.10	0.121	2.00	1.84	0.065	0.092	0.130	0.184	0.260	0.368	0.451
0.15	0.221	2.08	4.88	0.173	0.244	0.345	0.488	0.690	0.976	1.20
0.20	0.325	2.14	9.17	0.325	0.458	0.648	0.917	1.30	1.83	2.25
0.25	0.427	2.19	14.17	0.502	0.708	1.00	1.42	2.00	2.83	3.47
0.30	0.530	2.24	20.11	0.712	1.00	1.42	2.01	2.84	4.02	4.93
0.35	0.633	2.28	26.75	0.947	1.34	1.89	2.67	3.78	5.35	6.55

These calculations are based on a roughness coefficient (n) of 0.015. The actual gutter surface coefficient is probably equal to about 0.013. The higher value has been used to compensate for joint roughness and normal gutter debris.

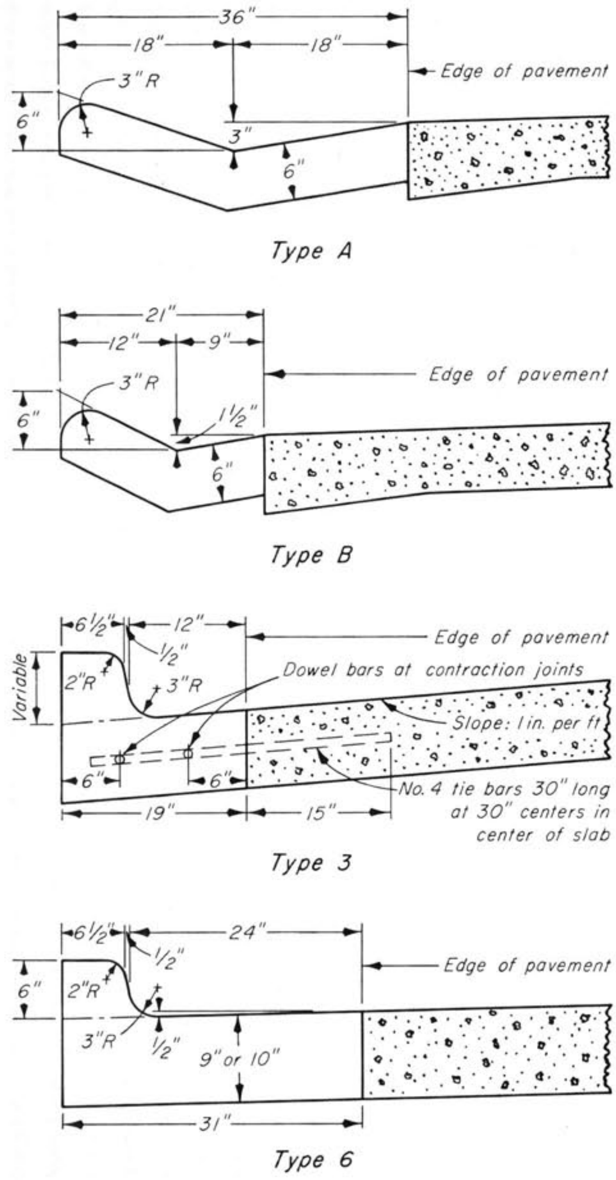


Fig. 47. Standard Gutter Sections, Illinois Division of Highways

gutter capacity, the Manning equation may be expressed as

$$Q = \frac{1.486A^{5/3}S^{1/2}}{np^{2/3}} \tag{16}$$

where Q = the rate of flow in cfs; A = cross section area of the flow prism in sq ft; S = longitudinal gutter slope in ft/ft; n = roughness coefficient; and p = wetted perimeter in ft.

Equation 16 indicates that flow varies directly with area and slope and inversely with roughness and wetted perimeter. The value of the wetted perimeter, p, is equal to the length of the flow prism boundary that is in contact with material whose roughness is equal to n. Thus, in a barrier-type curb, when the gutter flows at a depth greater than the gutter crossfall, the wetted perimeter is equal to the sum of the depth at the curb and the width of the gutter. To be completely accurate, the width of gutter is the slope distance from the face of the curb to the edge of the gutter. This may be taken as the horizontal gutter width for barrier-type gutters with moderate crossfall.

Theoretical rating data for the Type 6 gutter, used with the Type 3 inlet grate, is developed in Table 6 and presented graphically in Fig. 46. Each curve pertains to a specific longitudinal slope.

Similar computations have been completed for the gutter sections used with types 9, 10, and 11 inlet grates. The rating curves that result from these computations are also given in Fig. 46. Detailed dimensions of the gutter sections are shown on Fig. 47.

21. Pavement Flow Rating Curves

The rate of flow on the roadway pavement may also be determined by use of the Manning equation. In this case, the wetted perimeter is equal to the slope width of the flow prism.

Three pavement sections are widely used by the Illinois Division of Highways. The basic elements of these sections are presented in Table 7.

Calculations of rating data for the 12 ft parabolic pavement are indicated in Table 8. It includes flows up to 10 ft wide on seven longitudinal slopes. The results can be presented graphically as logarithmic rating curves. Figure 48 shows the relationships developed in Table 8. The individual curves are of identical shape, but, since the longitudinal slope is increased, the curve is displaced to the right, forming a family of curves.

Logarithmic rating curves for the 11 ft parabolic pavement and the 12 ft tangent pavement are also presented in Fig. 48.

A comparative study of the flow capacity of the three pavement sections has been made to simplify

Table 7

Elements of Pavement Sections

Half-width of Roadway	Surface Curve	Crown	Maximum Cross Slope
12 feet	Tangent	0.24 ft	.02 ft/ft
12 feet	Parabolic*	0.125 ft	.02 ft/ft
11 feet	Parabolic*	0.104 ft	.02 ft/ft

* The surface curve is specified as circular but a parabolic shape is used in construction. The difference in the two curves is not appreciable. Both parabolic pavements are built with the maximum cross slope in the outer one foot of the roadway.

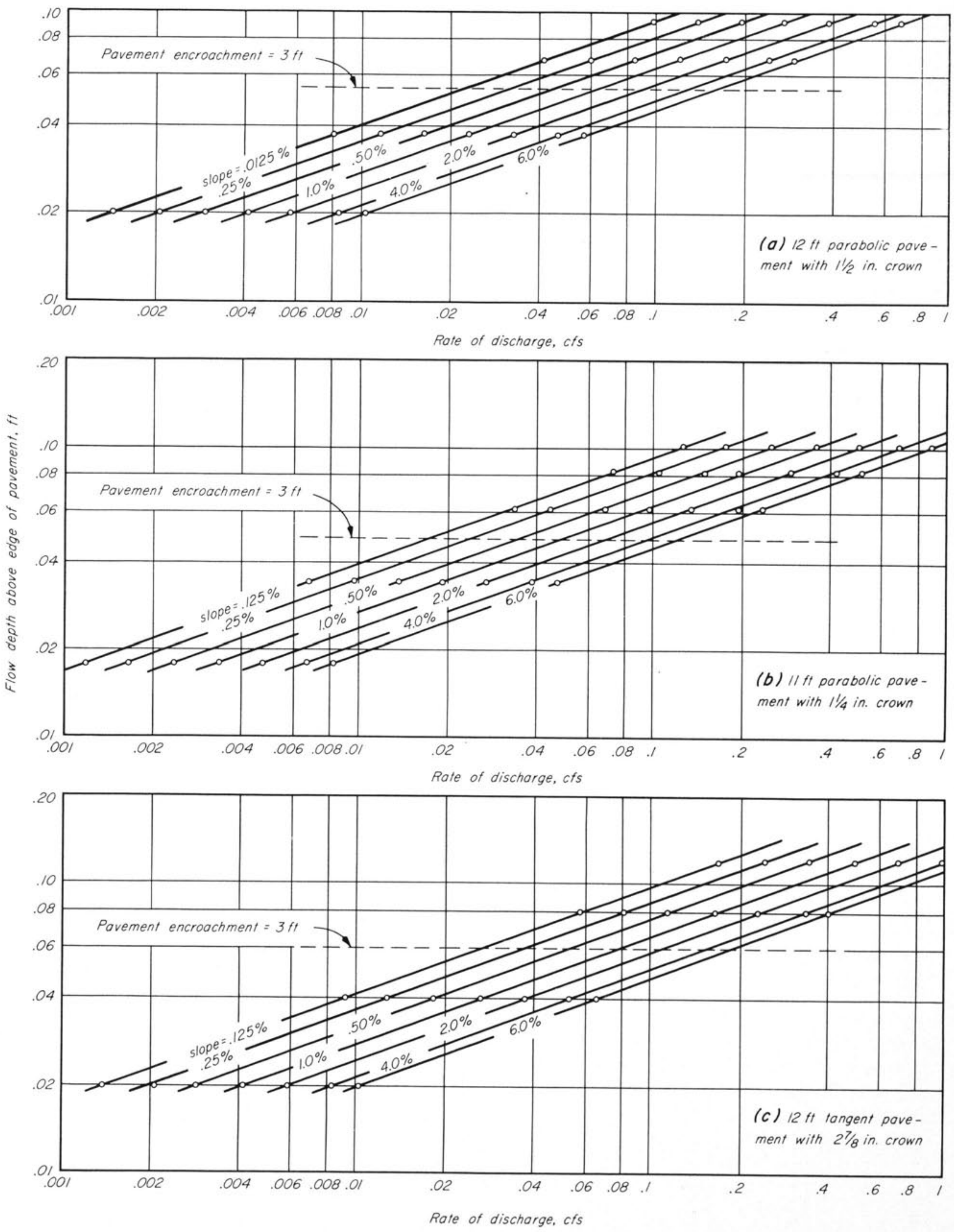


Fig. 48. Pavement Rating Curves

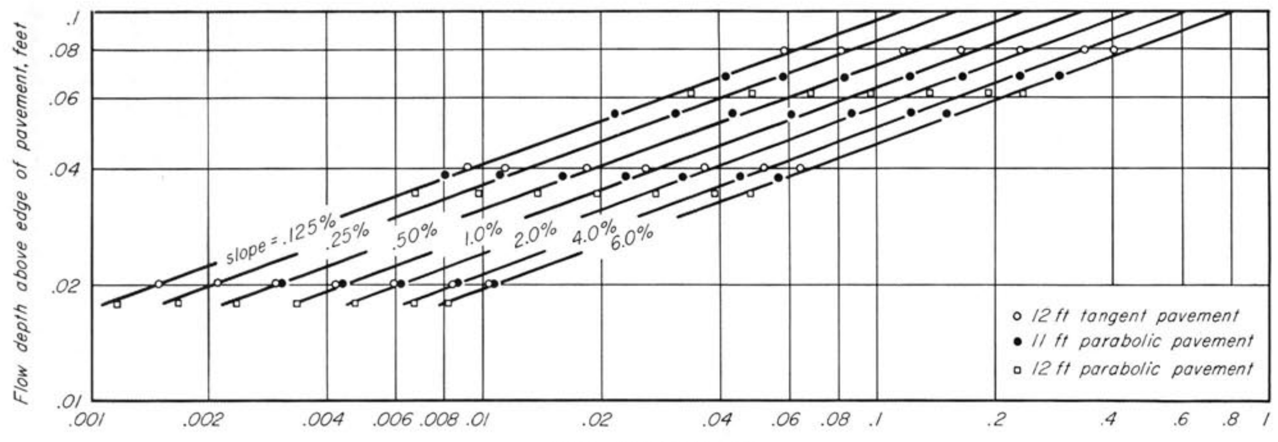


Fig. 49. Composite Pavement Rating Curves

the preparation and use of design curves. As indicated in Table 7, the maximum value of cross slope is the same for all three pavement types. In each case, the maximum cross slope occurs in the outside foot of pavement width.

Since the designer is usually restricted to utilizing only the outer 3 ft of the pavement for storm water flow, it is apparent that, for any given depth, the pavement flow prisms will be quite similar. Figure 48 shows that the capacity of the 3 ft flow prism is primarily a function of depth and that the shape of the pavement surface is not important. It also indicates that the flow capacities of the two 12 ft pavements are virtually identical. The differences between the 11 and 12 ft pavements are so small they may be neglected. It is concluded that the composite curves shown in Fig. 49 can be used for either of the three pavement sections.

22. Combined-Section Rating and Efficiency Curves

For any pavement slope and flow depth, summation of the pavement flow and the gutter flow yields the total rate of storm water flow.

In practice, the designer will determine the expected rate of flow by hydrologic analysis. After this value has been obtained, the appropriate combined-flow rating curve will indicate the depth at which the flow will occur in the given gutter section. Combined-flow rating curves for the four gutters tested are given in Fig. 50.

For example, assume that a flow of 0.92 cfs occurs in a Type 6 gutter when the longitudinal slope is 2.0%. Figure 49 indicates the depth of flow in the gutter will be 0.15 ft. Since the cross-fall in the Type 6 gutter is approximately 0.07 ft, the depth of water at the edge of pavement will be 0.08 ft. Figure 49 shows the rate of flow on the pavement is 0.24 cfs. By difference, the flow in the gutter prism is 0.67 cfs. This value may be checked by using Fig. 46.

Interception efficiency curves for the design flow sections can be calculated using the model data. Because the Type 3 and 11 inlets are normally used with curb openings, efficiency data are not given for these inlets with the opening closed.

Since the model was constructed of wood instead of concrete, and with a physical boundary at the pavement edge, it is necessary that the model data

Table 8

Calculated Rating Data — Parabolic Pavement 12 Feet Wide

Manning Equation — Various Longitudinal Slopes

Width of Flow ft	Maximum Depth ft	Area sq ft	$\frac{1.486A^{5/3}}{np^{2/3}}$	Rate of Flow for Indicated Slope 0.125% cfs	0.25% cfs	0.50% cfs	1.0% cfs	2.0% cfs	4.0% cfs	6.0% cfs
1.00	0.020	0.010	0.044	0.001	0.002	0.003	0.004	0.006	0.009	0.011
2.00	0.038	0.037	0.227	0.008	0.011	0.016	0.023	0.032	0.045	0.056
3.00	0.055	0.079	0.611	0.022	0.031	0.043	0.061	0.086	0.122	0.150
4.00	0.069	0.131	1.170	0.041	0.058	0.083	0.117	0.165	0.234	0.287
5.00	0.083	0.190	1.880	0.067	0.094	0.133	0.188	0.266	0.376	0.461
6.00	0.094	0.252	2.665	0.094	0.133	0.188	0.266	0.377	0.533	0.653
7.00	0.103	0.314	3.457	0.122	0.173	0.244	0.346	0.489	0.691	0.847
8.00	0.111	0.373	4.069	0.144	0.203	0.288	0.407	0.575	0.814	0.997
9.00	0.117	0.424	4.859	0.172	0.243	0.343	0.486	0.687	0.972	1.190
10.00	0.122	0.465	5.280	0.187	0.264	0.373	0.520	0.747	1.056	1.296

These calculations are based on a roughness coefficient (n) of 0.017 to allow for broomed surfaces, joints, and the very small depths of flow.

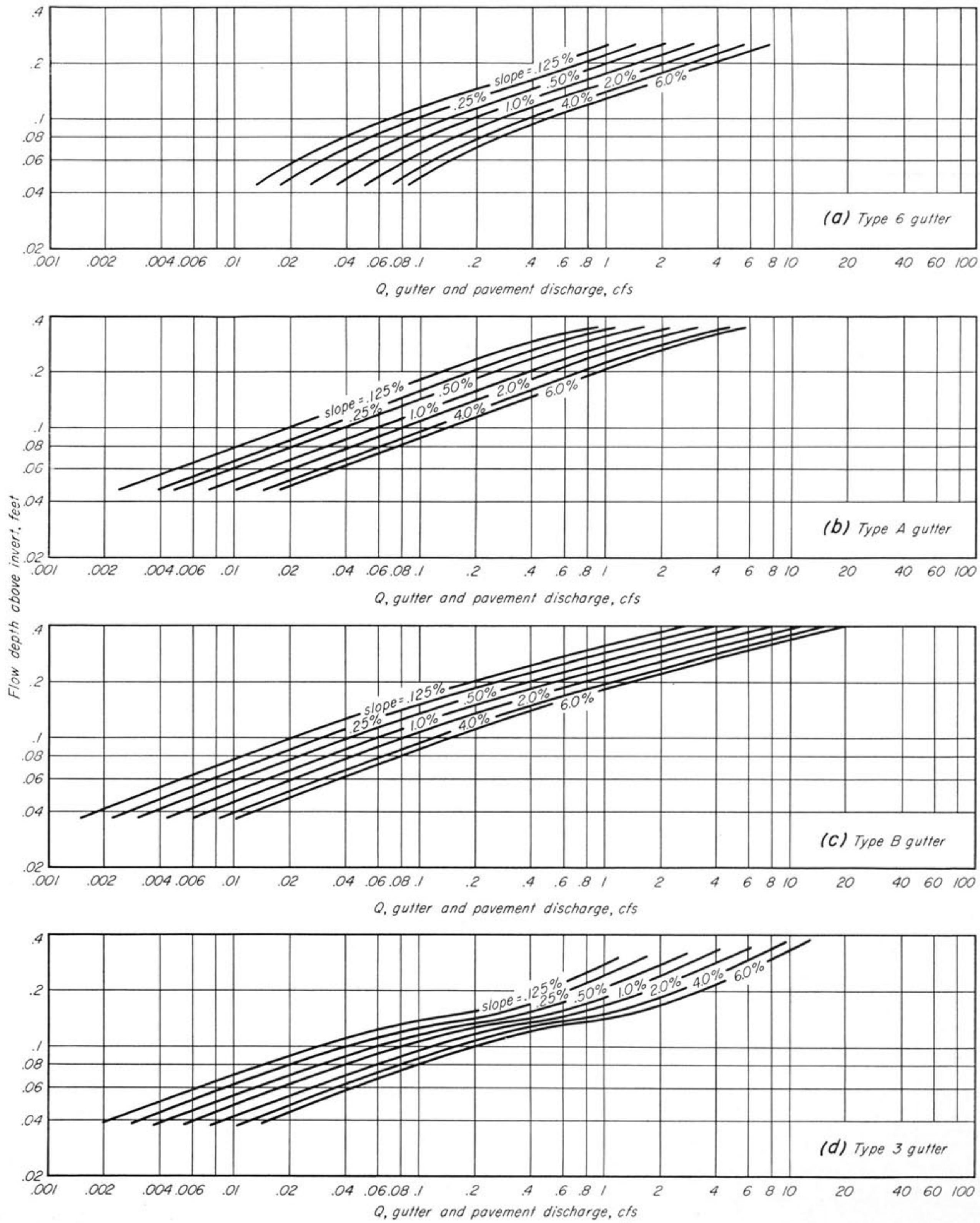


Fig. 50. Combined Section Rating Curves

Table 9

Calculation of Combined Efficiency

Type 3 Inlet in Type 6 Gutter — Various Longitudinal Slopes

Depth ft	Gutter Flow cfs	Flow to Inlet Rate cfs	Flow to Inlet Area sq ft	Velocity fps	Interception Efficiency %	Intercepted Flow cfs	Pavement Flow cfs	Combined Flow cfs	Combined Efficiency %
				Longitudinal Slope = 1.0%					
0.05	0.045	0.045	0.045	1.00	100	0.045	0.000	0.045	100
0.10	0.184	0.172	0.105	1.64	100	0.172	0.009	0.193	89
0.15	0.488	0.428	0.186	2.30	100	0.428	0.160	0.648	66
0.20	0.917	0.782	0.268	2.92	100	0.782	0.590	1.51	52
				Longitudinal Slope = 2.0%					
0.05	0.063	0.063	0.045	1.40	100	0.063	0.000	0.063	100
0.10	0.260	0.241	0.105	2.29	100	0.241	0.013	0.273	88
0.15	0.690	0.600	0.186	3.23	100	0.600	0.220	0.910	66
0.20	1.30	1.11	0.268	4.12	100	1.11	0.840	2.14	52
				Longitudinal Slope = 4.0%					
0.05	0.089	0.089	0.045	1.98	100	0.089	0.000	0.089	100
0.10	0.368	0.338	0.105	3.22	100	0.338	0.018	0.386	88
0.15	0.976	0.846	0.186	4.55	100	0.846	0.305	1.28	66
0.20	1.83	1.55	0.268	5.78	0.98	1.52	1.10	2.93	52
				Longitudinal Slope = 6.0%					
0.05	0.109	0.109	0.045	2.42	100	0.109	0.000	0.109	100
0.10	0.451	0.406	0.105	3.87	100	0.406	0.023	0.474	86
0.15	1.20	1.04	0.186	5.60	100	1.04	0.400	1.60	65
0.20	2.25	1.91	0.268	7.12	96	1.83	1.95	4.20	44

be adjusted for design use. Section 9 and Eq. 12 have established that, for any given gutter and inlet grate, the dynamic variable that most seriously affects interception efficiency is the gutter velocity. This can be used to calculate the interception efficiencies. For design use, the following paragraphs indicate the procedure adopted.

The interception data presented in Figs. 42 to 44 were determined using the model surfaces. Each point on the curves represents not only a given interception efficiency and flow rate, but also a certain depth, area, and velocity of gutter flow. Because of this relationship, a chart can be prepared to show the variation of the interception efficiency with the gutter velocity. Each chart will apply only to a specific gutter section, inlet grate, and longitudinal gutter slope. The curves resulting from this operation, using the Type 3 inlet frame with a parallel bar inlet grate and the curb opening, are shown in Fig. 51. Curves for slopes less than 1% are not included because in all cases the interception efficiency was 100%.

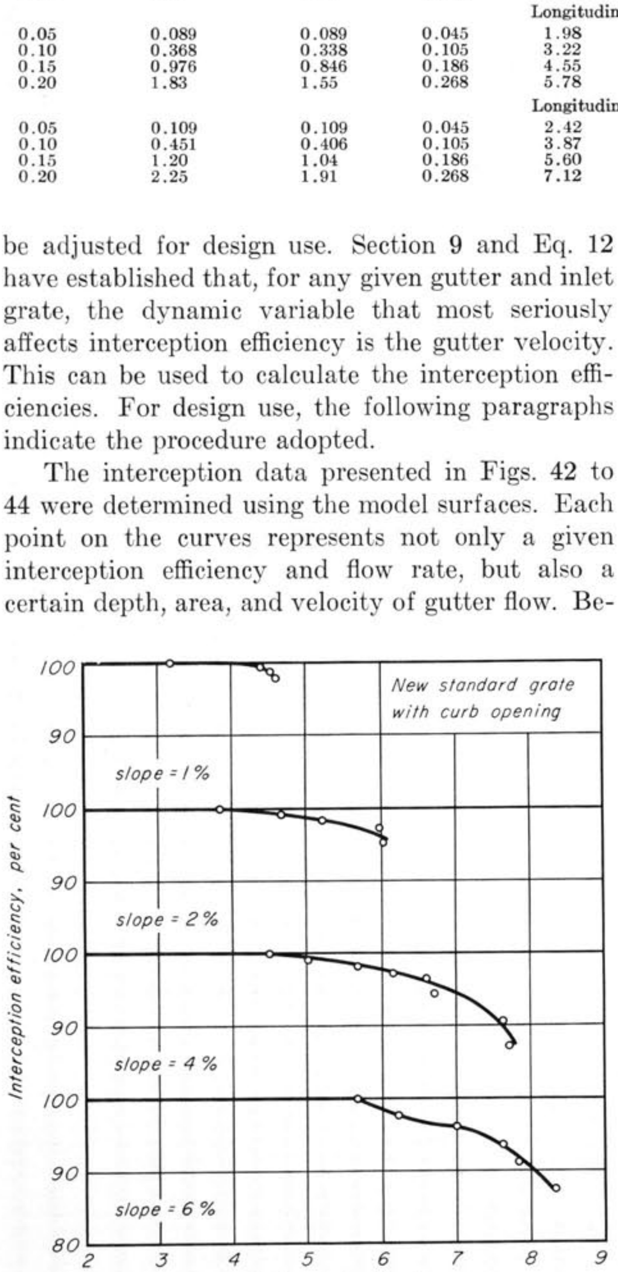


Fig. 51. Velocity-Efficiency Curves — Type 3 Inlet

These velocity-efficiency curves may be used to determine the combined interception efficiency for any gutter discharge by determining the portion of the combined flow that is in the gutter prism directly upstream from the inlet grate. The flow directly upstream from the inlet corresponds for all practical purposes to the flow in the laboratory calibration work. The portion of this flow that moves into the inlet may be determined by using the velocity-efficiency curves of Fig. 51. Finally, the ratio of the intercepted flow to the combined flow is interception efficiency. This figure can be expressed as either a decimal fraction or as a percentage.

Table 9 shows the computation of combined efficiency for the Type 3 inlet in the Type 6 gutter with longitudinal slope greater than 1.0%. Computations for slopes less than 1% have been omitted because the inlet intercepts all of the flow presented and use of the velocity criterion is not necessary.

To illustrate the procedure, assume that the depth of flow in the Type 6 gutter is 0.20 ft, and the longitudinal slope is 6.0%. The Table indicates that the gutter flow is 2.25 cfs (or from Fig. 46a).

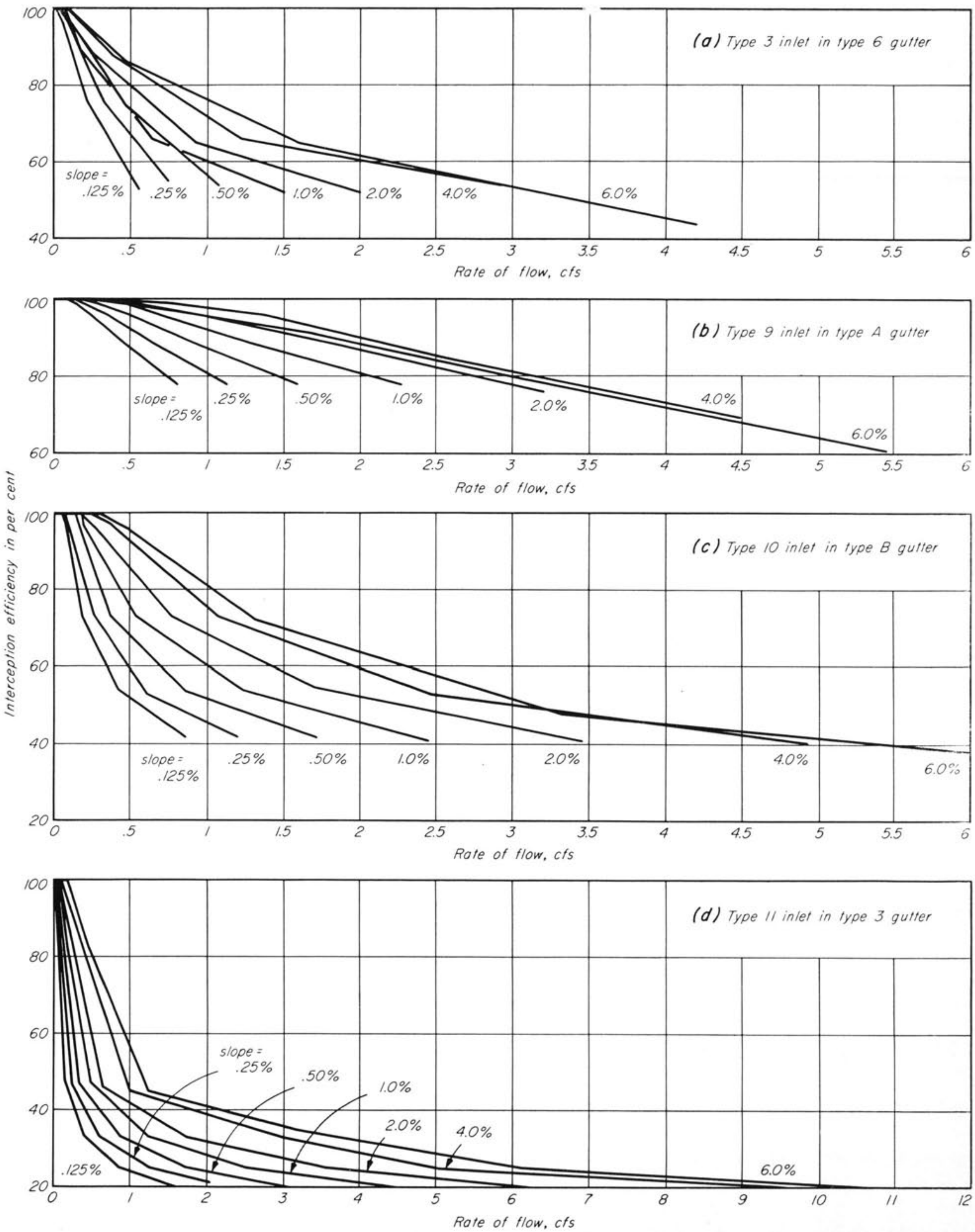


Fig. 52. Combined Section Efficiency Curves

Of this total flow, 1.91 cfs is in the gutter prism upstream from the inlet, and the velocity of flow is 7.12 fps. Figure 51 indicates that the interception efficiency is 96% and, therefore, the intercepted flow is 1.83 cfs.

If the amount of pavement water entering the inlet is negligible, then the intercepted flow rate is the same for both the gutter section and for the combined section.

The interception efficiency for the combined flow section may now be determined by dividing the intercepted rate of flow by the total rate of flow. Using the values of the example, the combined efficiency is equal to $1.83 \times 100/4.20 = 44\%$.

The efficiency data from Table 9 are presented graphically in Fig. 52. This type of curve will permit the designer to determine the intercepted flow for any total flow that may occur on the seven slopes that were considered. For slopes other than those indicated, straight-line interpolation will give the desired efficiency.

For example, assume that 0.75 cfs is flowing in a Type 6 gutter on a longitudinal slope of 3.0%. Figure 52 indicates that the efficiency on 2.0% slope is 69% and on 4.0% slope is 76%. Thus the 3.0% slope efficiency is 72%. Using this efficiency, the intercepted flow is $0.72 \times 0.75 = 0.54$ cfs, and a flow of 0.21 cfs will move past the inlet into the downstream gutter.

Combined efficiency curves for the Type 9, 10, and 11 inlets in their respective gutter sections are also given in Fig. 52.

The use of interception efficiency curves will permit the designer to evolve a rational design for gutter inlet systems when the gutter flow rate is known. Gutter flow rate determination is dependent upon an adequate hydrologic analysis. The hydrologic analysis is concerned with three major factors: the rainfall rate, the size of the drainage area, and the surfaces that compose the drainage area.

23. Determination of Design Runoff

If the rational equation (Eq. 1) is used to determine the design rate of flow, the effect of different types of surface treatment is included in the coefficient of imperviousness, C. The appropriate range of values of the coefficient has been determined on numerous occasions. The values shown in Table 10 have been accepted as being generally suitable for design purposes. It should be clearly understood that any empirical solution for the determination of runoff is completely dependent upon the judgment of the engineer making the analysis. The best procedure is to adopt an individual method of assessing the suitable coefficient. This value of the coefficient will usually be within the range indicated in Table 10. The individual engineer should evaluate his design in the light of actual precipitation events. In some cases it will probably be necessary to change the original concept for future designs. However, the accumulation of experience will lead to a completely satisfactory procedure. Actual observations should always take precedence over simplified analytical procedures.

Table 10

Values of the Coefficient of Imperviousness

Type of Surface	Coefficient Range
Asphaltic pavements	0.80–0.95
Concrete pavements	0.70–0.90
Gravel or macadam pavements	0.35–0.70
Impervious soils with turf*	0.30–0.55
Slightly pervious soils with turf*	0.10–0.30
Moderately pervious soils with turf*	0.00–0.10

* For slopes from 1% to 2%.

Except in special cases, design drainage areas are composed of more than one type of surface. An exception is the highway drainage area that is bounded by "V"-type gutters and shoulders that slope away from the pavement. In this case, the width of the drainage area is equal to the sum of the pavement half-width and the width of the gutter.

The size of the drainage area is equal to the product of the width and length. For Type A gutter and a 24 ft pavement, the drainage area is:

$$\text{Size of drainage area} = \frac{14 \times \text{length}}{43{,}560} \text{ (acres)}$$

Since the length of the drainage area is also the inlet interval, the drainage area may be determined from the expression $A = 3.21\ L \times 10^{-4}$ acres, where L is the inlet interval. This expression may be substituted in the rational equation to yield the rate of flow in terms of the imperviousness coefficient, rate of rainfall, and inlet interval.

The coefficient of imperviousness for the concrete pavement and gutter section is dependent upon the condition of the pavement. If there are numerous unsealed cracks and transverse joints, the coefficient may be as low as 0.60. However, it is not reasonable to use a reduced coefficient in design procedures. When the pavement is new, the poor joints will be non-existent and high runoff will occur, and even when inlets are being constructed

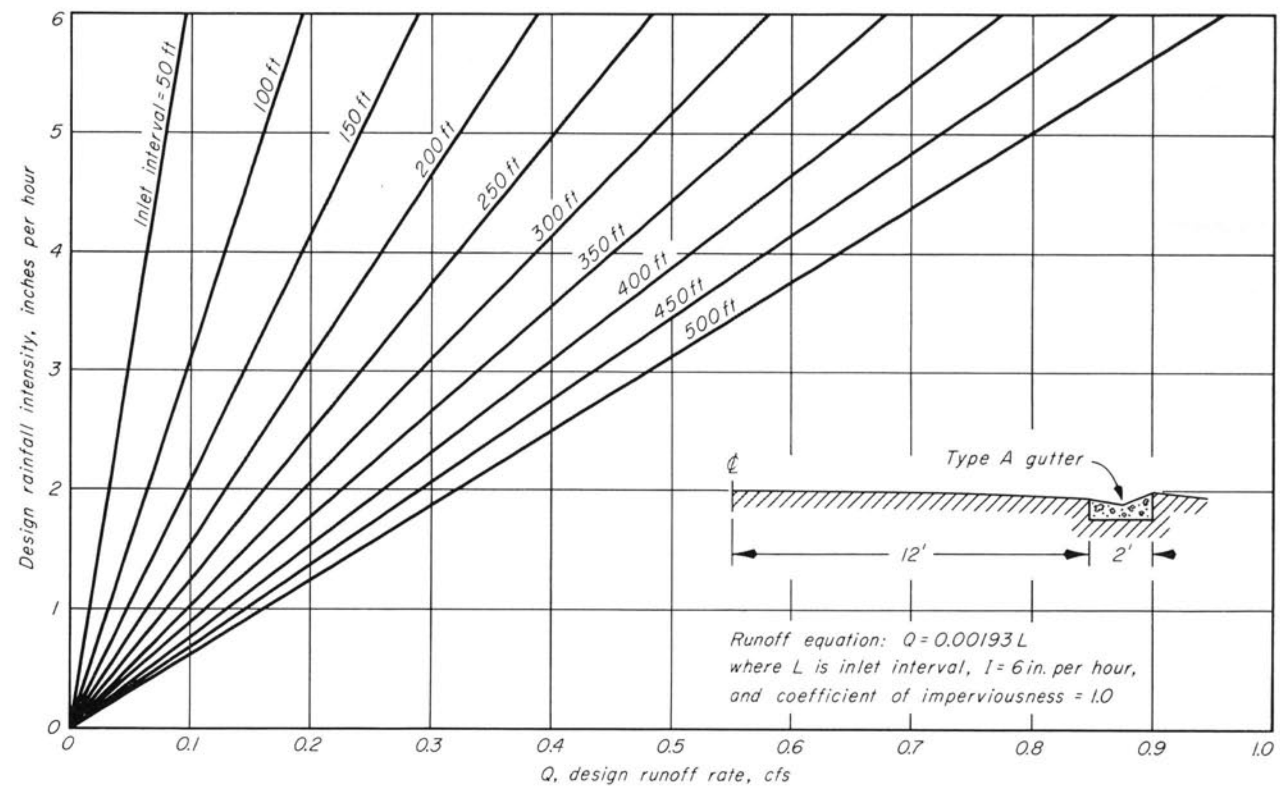


Fig. 53. Precipitation Runoff Chart — 12′ Tangent Pavement and Type A Gutter

adjacent to old pavements with many cracks and joints, the designer must provide for the additional runoff that will be generated after re-surfacing. Conservative design practice indicates that it is wise to consider the coefficient of imperviousness equal to 1.0. While this figure indicates a flow rate slightly greater than the theoretical maximum, several factors indicate the wisdom of such a selection. They include allowance for change in shoulder elevation, consideration of accuracy of rainfall prediction, and automatic design for slight debris effect at the inlet grate.

Introduction of the unity value of the imperviousness coefficient and the preceding equation for size of drainage area into the rational equation leads to the following basic equation for Type A gutter with a 24 ft pavement.

$$\begin{aligned} Q &= CIA \\ &= 1.0 \times I \times 3.21 \times L \times 10^{-4} \\ &= 3.21IL \times 10^{-4} \text{ cfs} \end{aligned} \tag{17}$$

The runoff chart based on Eq. 17 and shown in Fig. 53 pertains only to a paved section that is 14 ft wide. The chart permits the direct determination of runoff rate if both the rainfall intensity and the inlet interval are known. Thus, if a 4 in. design storm occurs on a roadway where the inlet interval is 300 ft, the total flow in the gutter will be 0.387 cfs.

The preceding example considered a drainage area composed of a single type of surface. Similar procedures allow the development of runoff charts for areas composed of several types of surfaces. For illustration, assume that a 24 ft pavement is bounded by parking lanes 8 ft wide and a Type 6 curb and gutter section. This type of construction is usually confined to urban streets and highways. In most urban construction, the street gutter carries runoff from parking strips, sidewalks, and front yards, as well as that generated on the pavement surface. In this case, it is necessary to compute a composite value of the imperviousness coefficient. This is done most easily when the distribution of types and lateral extent of surfaces is assumed to be uniform along the length of the roadway. Only in very special cases is it necessary to make individual allowance for driveways, walks, and other features that conflict with the assumption of longitudinal uniformity. Table 11 indicates the develop-

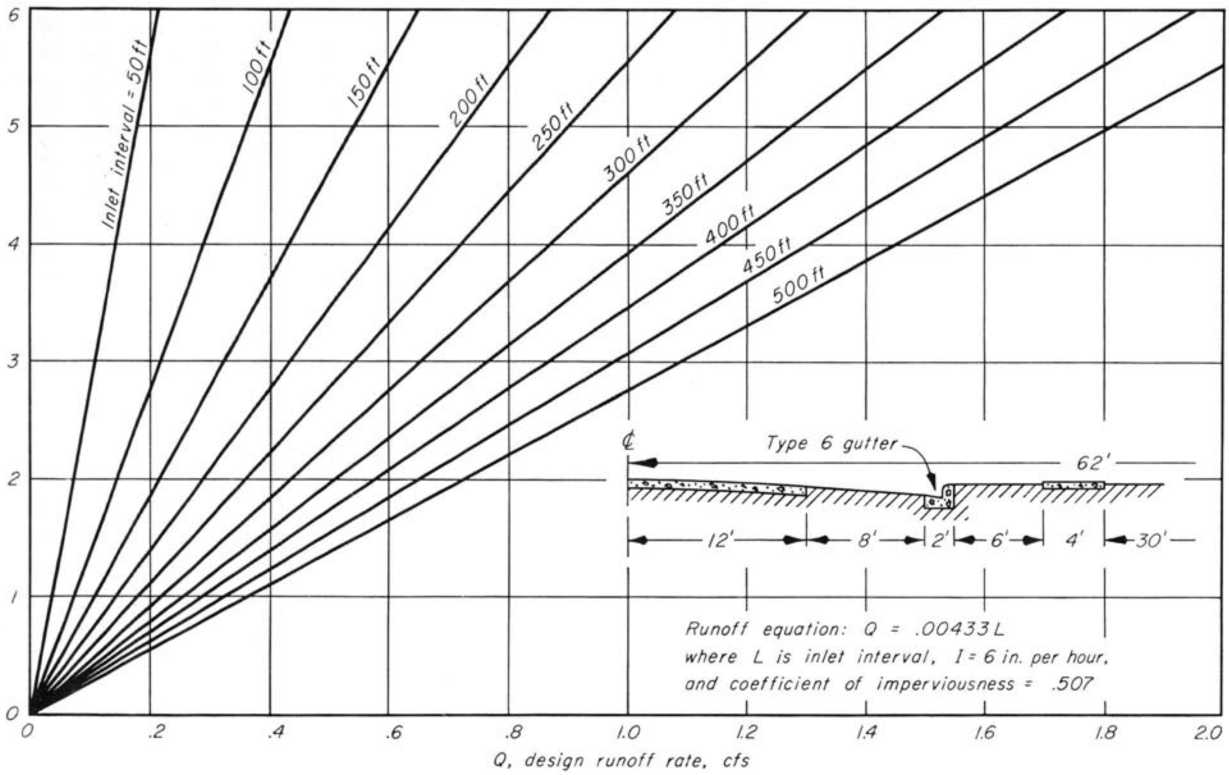


Fig. 54. Precipitation Runoff Chart — 12' Tangent Pavement and Type 6 Gutter

Table 11

Composite Imperviousness Coefficient

Type of Surface	Width	Coefficient	Product
Pavement half-width	12	1.00	12.00
Parking pavement	8	1.00	8.00
Type 6 gutter	2	1.00	2.00
Parking strip — turf	6	0.15	0.90
Sidewalk	4	1.00	4.00
Front yard — turf	30	0.15	4.50
Totals	62		31.40

$$\text{Composite Coefficient} = \frac{31.40}{62} = 0.507$$

ment of a composite value of the imperviousness coefficient for a typical urban situation.

Introduction of the composite coefficient and the new drainage area function into the rational formula leads to the following design equation:

$$\begin{aligned} Q &= CIA \\ &= 0.507 \times I \times 1.43 \times L \times 10^{-3} \\ &= 7.25IL \times 10^{-4} \text{ cfs} \qquad (18) \end{aligned}$$

Equation 18 yields a precipitation runoff chart for the specific conditions of the example, which is shown in Fig. 54. It indicates that when a 4 in. per hour design storm occurs on a roadway with inlet interval equal to 300 ft, the generated runoff will be 0.87 cfs.

It should be noted that the runoff from the Type 6 gutter example is approximately 125% greater than that from the Type A gutter example. Also, the impervious area of the Type 6 example is 117% greater than corresponding area of the Type A example. The similarity of both figures indicates that the turf area does not contribute a significant portion of the total precipitation runoff. This should be anticipated because of the ratio of the basic imperviousness coefficients.

24. Precipitation and Frequency

The design precipitation rate depends upon two factors, design frequency and duration time. Design frequency is important because, theoretically, the design standards will be violated only once in the frequency period. For example, assume that a gutter inlet system is designed so that a storm with a frequency of ten years will cause water to encroach on only the outer 3 ft of the pavement. This degree of encroachment is a design standard. For this system, the designer is justified in assuming that such encroachment will occur, on the average, once every ten years. On the tenth year however, the design will not handle the runoff from a single

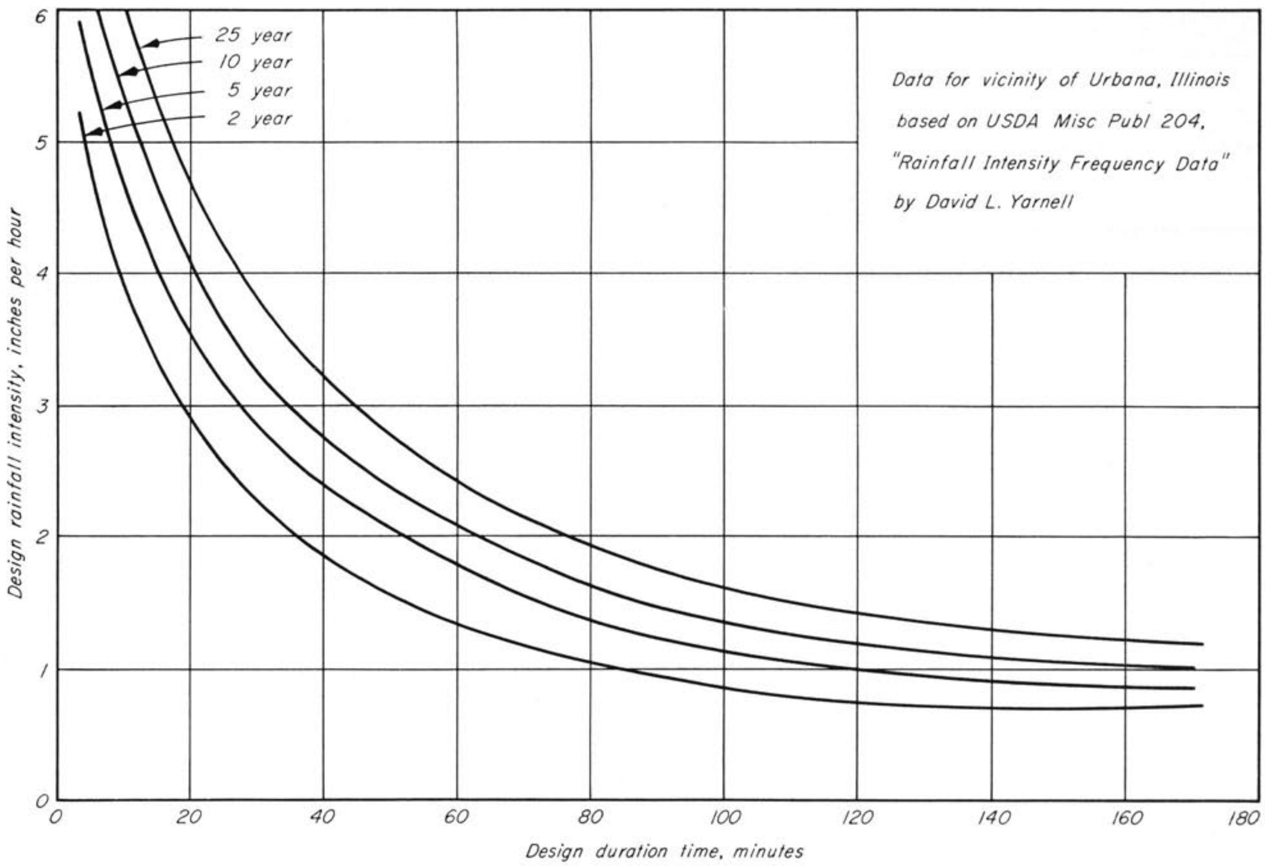


Fig. 55. Rainfall Frequency Curves

storm without allowing more than 3 ft of encroachment on the roadway surface.

It must be understood that precipitation events are not aware of these arbitrary concepts, and it is perfectly possible to experience two ten-year storms in a single year. On the average basis, however, the frequency concept is fully justified and essential to a sound and economical design.

The importance of the design limitations varies not only with traffic importance and volume, but also with regard to the amount of resulting damage to the roadway. The capacity of an upgrade inlet may be surpassed without damage because the water bypasses the inlet and is presented to the next inlet in the series, an action which may be completely acceptable at the upgrade inlet. If, however, the inlet is located at the bottom of a vertical curve on a fill section of roadway, the same lack of inlet capacity is prohibitive. In this case, ponding may occur to such an extent that water flows over the shoulder and down the fill slope. The result is a troublesome maintenance problem and, under severe circumstances, the loss of a section of roadway.

The preceding example is not intended to recommend the use of different design frequencies for different portions of the gutter inlet system, although in certain cases this may be justified. Design frequency determination should be a policy-type decision based upon the importance of the particular highway from the standpoint of both traffic and capital investment.

The second factor influencing selection of the design precipitation rate is duration time. Duration time is important because, for any given frequency, the rate of precipitation varies inversely with length of precipitation time. This is shown graphically on the rainfall-frequency chart in Fig. 55.

When the rational equation is used for the determination of runoff, it is assumed that the storm duration time is equal to the time of runoff concentration. The time of concentration is defined as the time required for water falling at the most chronologically remote point of the drainage area to reach the point of outlet. Thus, for a given rainfall intensity, the rate of flow from a drainage area will increase with respect to time until the time of concentration is achieved. From this time on, the rate of outflow will be constant until the rate of rainfall is changed. Obviously, when the duration time is equal to the time of concentration the maximum runoff will occur.

The time of concentration for any area must be estimated. Consider a drainage area composed of the Type A gutter and pavement with a half-width equal to 12 ft. Assume the drainage area is 400 ft long and the gutter slope is 1.5%. The time of concentration is the sum of the time required for water to move across the pavement to the gutter, plus the time required for flow to move through the 400 ft of gutter. The transverse pavement flow time is usually assumed to be about 4 min. If the velocity of flow in the gutter is 1.5 fps, then 267 sec, or 4.4 min, will be required for gutter travel. The time of concentration is equal to about 8.4 min. Figure 55 indicates that the two-year design rainfall intensity is 4.2 in. per hr. Introduction of this value in the rational equation, and assuming 100% runoff, yields the following design flow rate for the drainage area.

$$\begin{aligned} Q &= CIA \\ &= \frac{1.0 \times 4.2 \times 14 \times 400}{43{,}560} \\ &= 0.540 \text{ cfs} \end{aligned}$$

The calculated runoff rate may be verified using the runoff chart of Fig. 53.

25. Carryover Flow

The amount of flow that bypasses an inlet is known as carryover flow. Carryover flow occurs because of lack of inlet capacity, or because flow on the pavement is not presented to the inlet opening.

When design flows occur in a street drainage system, all upgrade inlets in the system should contribute carryover flow to the next inlet downstream. Only the inlet located at the low point in the roadway grade should be designed to receive all of the flow that is presented to it.

Carryover flows are necessary and desirable when they are caused by the passage of pavement water around the inlet. This is because the encroachment of flow on the pavement is accompanied by greater concentrations of flow in the gutter prism. Under design conditions, discharge carryover flows will be greatest on steep roadway slopes, just as the intercepted flows will be greatest on the steep slopes.

It is essential that carryover flows be considered in the design of gutter inlet systems. The occurrence of a carryover flow requires that downstream inlet intervals be reduced if design limits are not to be exceeded.

This may best be illustrated by an example. Suppose that the maximum allowable flow in a Type A gutter is 0.87 cfs. If the longitudinal slope is 0.5%, the depth of flow will be 0.30 ft (Fig. 49). This rate of flow represents the runoff from 500 ft of pavement with half-width equal to 12 ft when the precipitation intensity is equal to 5.45 in. per hr (Fig. 53). If this flow is presented to a Type 9 inlet, the interception efficiency will be 89% (Fig. 52). Thus, the intercepted flow will be equal to 0.77 cfs and the carryover flow will be .10 cfs. The carryover flow will originally be on the pavement, but shortly after passing the inlet, it will move into the gutter and be presented to the next inlet in the system.

Because of the presence of the carryover flow, only 0.77 cfs of storm water may be added to the gutter without exceeding the maximum design flow of 0.87 cfs. As indicated on Fig. 53, a discharge rate of 0.77 cfs represents the runoff generated by about 440 ft of the pavement. In this case, when there is no carryover the inlet interval may be 500 ft, but when there is carryover the interval must be reduced to 440 ft.

The preceding example indicates the fallacy of constructing inlets on a continuous grade with equal inlet intervals. A continuation of the example will indicate the wisdom of permitting carryover flows to occur. The capacity of a Type 9 inlet, with longitudinal slope of 0.5%, is 0.13 cfs when there is zero carryover. If the same roadway was sufficiently long to generate a total runoff of 3.40 cfs, 26 inlets would be required to intercept the total flow. If, however, the inlets are designed to operate with an interception efficiency of 90% (so that there will be 10% carryover), the flow intercepted by each inlet will be 0.83 cfs, requiring only 5 inlets to intercept the total flow. This demonstrates the wisdom of designs that permit appreciable rates of carryover flow.

The factor that determines the permissible amount of carryover flow is the design limit on pavement encroachment. The efficiency of the hydraulic design is a direct function of the amount of water that may be carried on the roadway pavement, which is a matter of policy dependent upon pavement surface, traffic count, and roadway importance.

26. Pavement Slope

The longitudinal slope of the roadway pavement is of utmost importance to the design of an efficient inlet system. Since the longitudinal pavement slope and gutter slope are usually equal, the pavement slope is used to determine the depth of flow and the velocity for any given gutter discharge. It is also used to determine the time of concentration when calculating rates of precipitation runoff. These uses of the longitudinal slope have been discussed in preceding portions of this report.

The pavement slope is of further importance if the longitudinal slope is large when compared to the transverse slope. When the longitudinal slope is more than four or five times as large as the transverse slope, the drainage area tributary to the first in a series of inlets must not be considered rectangular. Under such conditions of slope, the drainage area is at best trapezoidal, and may even be triangular.

When rectangular drainage area procedures are applied to inlet systems that serve steep pavement slopes, two malfunctions will occur. The upstream inlet will intercept less than the design flow, and the downstream inlet will be forced to receive more than the design flow. When the downstream inlet is capable of receiving the overload, little damage results and the only evidence of the inadequate design is temporary flooding of the roadway. When the downstream inlet cannot accommodate the overload, serious damage may occur in the form of severely eroded embankments, flooded structures adjacent to the right-of-way, or saturated and damaged sub-bases.

Experimental evidence substantiates the theoretical conclusion that pavement flow occurs at an angle of 45° when the cross slope is equal to the longitudinal slope. When this is true, the length of roadway that is required for water to move from the centerline of the roadway to the gutter is equal to the half-width of the pavement.

When the longitudinal slope is significantly greater than the transverse slope, the relation between the longitudinal and transverse distances is not linear. Tests conducted on a model pavement,[11] with steady flow, indicate that the angle of flow is a power function of the slope ratio. The following expression has been obtained using a model with 2% transverse slope and variable longitudinal slope.

$$\text{tangent } \alpha = 0.78 \left(\frac{S_L}{S_C} \right)^{1.2} \qquad (19)$$

where α is the angle in the horizontal plane between the flow path and a line normal to the centerline, S_L is the longitudinal slope of the roadway, and S_C is the transverse slope of the roadway.

If the transverse pavement slope is equal to 2% and the roadway half-width is 12 ft, Eq. 19 may be expressed as

$$l_p = 1030 \; S_L^{1.2} \qquad (20)$$

where l_p is the length of pavement that is required for flow to move from the roadway centerline to the gutter. Table 12 indicates the length of pavement that is required for various longitudinal roadway slopes.

Table 12

Cross-Over Distance for Selected Slopes

Longitudinal Slope %	Longitudinal Slope ft/ft	Roadway Half-width ft	Length for Cross-over ft
4.0	.04	12.0	21.6
6.0	.06	12.0	35.0
8.0	.08	12.0	49.5
10.0	.10	12.0	65.0
12.0	.12	12.0	80.5
16.0	.16	12.0	113.0

The effect of a steep pavement upon inlet design may be demonstrated by considering a section of tangent-crown roadway with a half-width of 12 ft and a Type B gutter. When the longitudinal slope is 12%, this gutter, flowing just full, has a capacity of about 0.38 cfs. Flow will not encroach on the roadway surface.

The design runoff chart, which is based on rectangular drainage areas, will indicate that this flow is generated by a roadway length of 250 ft when the rainfall intensity is 4.7 in. per hr. Thus, using the rectangular criteria, the designer would locate the inlet 250 ft from the roadway summit and would expect to intercept virtually all of the flow in the gutter.

Examination of the actual path of flow on the pavement shows that the rectangular criteria must not be used when the longitudinal slope is great. Table 12 indicates that when the slope is 12%, a distance of 80.5 ft is required for flow to move from the roadway centerline to the gutter. Because of this, runoff from a triangular area 80.5 ft long by

12 ft wide, located upgrade from the inlet, cannot be presented to the inlet. This area represents more than 16% of the total tributary area. The flow that will actually be presented to the inlet will be about 0.32 cfs. The remainder of the original flow will continue downgrade and will overtax the following inlets in the system.

It should be realized that the preceding example is based on a tangent-crown roadway on continuous grade. Roadways with circular crown will cause more trouble because the average cross slope is significantly less. It is not at all unreasonable to expect that cross-over lengths of 200-300 ft will be encountered when circular crowns are employed on steep slopes.

VI. AN APPLICATION OF THE DESIGN CRITERIA

Application of the information developed in this report may best be illustrated by the hydraulic design of a typical roadway gutter system. The roadway selected for this purpose is a straight bituminous surface, 24 ft wide, with Illinois Division of Highways Type A gutters on both sides of the pavement. The origin of the design section, Station 0+00, is at the bottom of a vertical curve that is 400 ft long. The terminus of the design section, Station 25+00, is at the top of another 400 ft vertical curve. The two vertical curves are connected by a tangent section whose longitudinal slope is 1.0%.

Consideration of the roadway and surrounding topography indicates that all of the intercepted flow should be discharged at a stream that crosses the right-of-way at Station 0+00. Because of this requirement, the surface drainage design must begin at the top of the roadway drainage area.

Since the vertical curve that centers at Station 25+00 is 400 ft long, only 200 ft of roadway at the upper end of the drainage area is on a slope of less than 1.0%. It is apparent that the first inlet in the system will be located on the tangent section.

27. The Initial Inlet

The first step in the design solution is to determine the time of flow in the roadway gutter of the first tributary drainage area. This is done by assuming that the velocity of flow in this section of gutter is a function of the average slope, 0.5%. The Manning equation indicates that the average velocity will be

$$\begin{aligned} V &= \frac{1.486}{n} R^{2/3}S^{1/2} \\ &= \frac{1.486}{.015} \times .123^{2/3} \times .005^{1/2} \\ &= 2.0 \text{ fps} \end{aligned} \tag{21}$$

This figure will be used in the tabular development of the inlet interval.

The maximum permissible depth of flow at the inlet is 0.30 ft. Greater flow depths would cause storm water to encroach more than 3 ft on the roadway pavement. Because of this criterion, the maximum allowable flow in the gutter is 1.20 cfs (Fig. 50).

Table 13

Initial Inlet Intervals for Runoff Equal to 1.20 cfs

Inlet Interval ft	Rainfall Intensity in. per hr	Design Duration min	Gutter Flow Time min	Time of Concentration min
1400	2.67	34	11.7	16
1200	3.11	26	10.0	14
1000	3.74	18	8.3	12
800	4.67	10	6.7	11
700	5.34	6	5.8	10

The various combinations of inlet interval and rainfall intensity that will produce a runoff of 1.20 cfs may be calculated using Eq. 17. Introduction of the flow rate and transposing yields the following expression

$$IL = \frac{1.20 \times 10^4}{3.21} = 3{,}740 \tag{22}$$

Several intensity-length combinations are presented in the left two columns of Table 13.

The third column of the table presents the design duration time that corresponds to the rainfall intensity of column 2. These data were taken from Fig. 55 and apply specifically to the vicinity of Urbana, Ill., and to a 5-year frequency.

Column 4 of the table indicates the time required for flow to move through a gutter whose length is equal to the inlet interval. These figures are obtained by dividing the inlet interval by the flow velocity and expressing the result in minutes.

Column 5 of the table is the time of concentration for the particular inlet interval. Each figure is equal to the sum of the gutter flow time plus four minutes. The four minute increment allows for the time of flow across the highway slab.

The table indicates that when the inlet interval is slightly greater than 800 ft the actual flow time is just equal to the allowable duration time. Since the two times are equal, the initial inlet should be located 800 ft downslope from the summit or at Station 17+00. It should be noted that had the

Table 14

Inlet Intervals for Runoff Equal to 1.08 cfs and Gutter Flow Equal to 1.20 cfs (Slope 1.0%)

Inlet Interval ft	Rainfall Intensity in. per hr	Design Duration min	Gutter Flow Time min	Time of Concentration min
1000	3.36	22	4.9	15
800	4.20	14	3.9	14
600	5.60	5	3.0	13

two times not been substantially equal, the proper inlet interval could be obtained by interpolation. The interception efficiency of Inlet No. 1 will be 90% (Fig. 52b), and the intercepted flow will be 1.08 cfs. The carryover flow will be 0.12 cfs.

28. Successive Inlets

The second inlet will be located downgrade from the initial inlet at a distance such that the total flow in the gutter will again be 1.20 cfs. Since 0.12 cfs of storm water flows to the second inlet from the first inlet, the pavement runoff must be limited to 1.08 cfs. Table 14 indicates the combinations of inlet interval and rainfall intensity that will produce a flow of 1.08 cfs. In this case, the time of concentration is the sum of the 10 min flow time from the first inlet interval and the gutter travel time.

The Table shows that the second inlet should be located 800 ft downgrade from Inlet No. 1, or at Station 11+00. The preceding type of calculation applies to all other inlets that are located on the 1.0% grade tangent. The tangent inlet locations and characteristics are summarized in Table 15. It may be noted that the third inlet is located 180 ft upstream from the bottom of the grade and 20 ft below the point of tangency with the lower vertical curve.

There are two important factors that must be considered in locating the last two inlets. The first is that the inlet at the bottom of the drainage area (Inlet No. 4, Station 0+00) must serve drainage areas on both sides of Station 0 + 00. The second factor is that Inlet No. 3 should be located close to the point where the gutter velocity will decrease due to the change in slope, for the following reasons:

1. For a given flow rate, when the gutter velocity diminishes, the flow area increases. The increase in flow area makes efficient interception more difficult.
2. When the gutter velocity diminishes, the ability to transport entrained sediment decreases. Unless the inlet is located upstream from the point of critical velocity, material will be deposited in the gutter and cause flooding of the roadway.

Table 15

Summary of Inlet Locations

Inlet Number	Station ft	Distance Between ft	Total Flow cfs	Intercepted Flow cfs	Carryover Flow cfs
		800			
1	17+00		1.20	1.08	0.12
		800			
2	11+00		1.20	1.08	0.12
		920			
3	1+80		1.20	1.08	0.12
		180			
4	0+00		0.325	0.325	.00

Based on these criteria, Inlet No. 3 should be located at the point where the gutter velocity is still capable of moving sand and coarse silt. The limiting velocity for this material is approximately 1.50 fps in a relatively smooth gutter. The longitudinal slope that will maintain this velocity in a Type A gutter is about 0.5%.

Inlet No. 4, located at the bottom of the sag, will intercept a total flow of 0.325 cfs. This flow is composed of 0.12 cfs, carryover from Inlet No. 3, and 0.205 cfs runoff from the pavement. The pavement runoff is determined by adding the travel time from Station 1+80 to 0+00 (1.5 min) to the total travel time to Inlet No. 3 (Station 1+80, 18.5 min). Entering Fig. 55 with the 20 min duration time yields a rainfall rate of 3.55 in. per hr for the 5-year frequency. Solution of Eq. 17, for this rainfall rate and the 180 ft interval gives the pavement flow of 0.205 cfs.

Table 15 presents a summary of the four inlet locations and flow characteristics. It should be understood that the table applies to only one-half of the pavement width. Since both geometric and dynamic conditions are similar, the other half of the roadway must also be provided with four gutter inlets.

Material in this section of the report (Sec. 28) applies to design of inlets in series and illustrates the influence of carryover flows. Inlets designed on an individual basis, whether they are isolated or form a part of a series, should be designed as an initial inlet.

The reader is cautioned that the preceding example is intended to illustrate the use of the design concepts developed in this report. It is presented to bring together the various component parts of the design problem and is not intended to indicate the best application procedure.

The best design procedure for any engineer is the one that fits his particular system and objective. This report is intended to supply basic information toward better inlet design. The integration of that information into office procedure should be accomplished by the individual utilizing basic relationships. Substantial economies will result from instituting realistic design procedures.

BIBLIOGRAPHY

1. Conner, N. W., "Design and Capacity of Gutter Inlets," North Carolina State College Record, Vol. 44, No. 11, Engineering Experiment Station Bulletin No. 30, July 1945.
2. Guillou, J. C., and Chow, V. T., "Desilting Structures for Highway Drainage Systems," University of Illinois, *Civil Engineering Studies,* Hydraulic Engineering Series No. 3, June 1954.
3. Guillou, J. C., "Hydraulic Flow Characteristics of a Funnel Type Street Inlet," Thesis presented to the Graduate College, University of Illinois, Urbana, Illinois, 1954.
4. Hicks, W. I., "Runoff Computations and Drainage Inlets for Parkways in Los Angeles," *Proceedings of the Twenty-Fourth Meeting of the Highway Research Board,* December 1944.
5. Jennings, A. H., "Maximum 24-hour Precipitation in the United States," U. S. Dept. of Commerce, Weather Bureau *Technical Paper No. 16,* 1952.
6. Larson, Curtis L., "Grate Inlets for Surface Drainage of Streets and Highways," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, *Bulletin No. 2,* June 1949.
7. Larson, Curtis L., "Investigation of Flow Through Standard and Experimental Grate Inlets for Street Gutters," Project Report 3 (and Supplement), St. Anthony Falls Hydraulic Laboratory, University of Minnesota, 1947.
8. Tapley, G. S., "Hydrodynamics of Model Storm Sewer Inlets Applied to Design," *Transactions,* American Society of Civil Engineers, Paper No. 2184, Vol. 108, 1943.
9. Yarnell, D. L., "Rainfall Intensity-Frequency Data," United States Department of Agriculture, Miscellaneous Publication No. 204, August 1935.
10. The Johns Hopkins University, "The Design of Storm-Water Inlets," Department of Sanitary Engineering and Water Resources, June 1956.
11. The University of Illinois, Hydraulic Engineering Laboratory, "Pavement Slope Model, Preliminary Data," August 1956, unpublished.

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